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Demonstrating Nonhexavalent Chrome Steel Conversion Coatings on Stryker High Hard Armor Steel Hatches

by John V. Kelley and Thomas Braswell

ARL-TR-6789

January 2014

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Army Research Laboratory

Aberdeen Proving Ground, MD 21005-5069

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE			3. DATES COVERED (From - To)	
January 2014	Final			1 January 2010–31 December 2012	
4. TITLE AND SUBTITLE Demonstrating Nonhexavalent Chrome Steel Conversion Coatings on Stryker High Hard Armor Steel Hatches					
6. AUTHOR(S) John V. Kelley and Thomas Braswell					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: RDRL-WMM-C Aberdeen Proving Ground, MD 21005-5069					
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)					
10. SPONSOR/MONITOR'S ACRONYM(S)					
11. SPONSOR/MONITOR'S REPORT NUMBER(S)					
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT High hard armor steels are used on many tactical vehicles, such as the Stryker and the mine-resistant, ambush-protected vehicle. Although they provide good protection against armor-piercing threats, these steels corrode rapidly without the use of a good corrosion protective coating. Corrosion on military ground vehicles increases the infrared signal from the vehicle that the topcoat camouflage usually inhibits, making the vehicle more vulnerable to detection by the enemy. Stryker vehicles are prohibited from using hex-chrome and are currently coated without any pretreatment or conversion coating. The products demonstrated here will satisfy the hexavalent chrome prohibition while minimizing environmental impact and worker safety. This demonstration plan is designed to generate the data necessary for authorization and implementation decisions by appropriate authorities within the U.S. Department of Defense.					
15. SUBJECT TERMS hexavalent chrome, steel pretreatments, high hard armor corrosion, Stryker					
16. SECURITY CLASSIFICATION OF: a. REPORT b. ABSTRACT c. THIS PAGE Unclassified Unclassified Unclassified			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 98	19a. NAME OF RESPONSIBLE PERSON John V. Kelley

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1. Introduction

1.1 Background

The high hard armor steels used on Strykers and the mine-resistant, ambush-protected (MRAP) vehicles and a wide range of other systems provide good protection against armor-piercing threats. However, these steels corrode rapidly without good corrosion protective coatings. High hard armor (HHA) is also susceptible to structural damage from environmentally assisted cracking (EAC) whenever residual stresses are present, especially when inferior plate cutting and welding procedures are used. For decades, these corrosion problems have been well documented for HHA steels. More recently, photos of newly fabricated, unfielded MRAP vehicles showing significant corrosion have circulated within the U.S. Department of Defense (DOD) community. While some may dismiss this rusting as merely cosmetic corrosion, the reality is that such corrosion on military ground vehicles increases the infrared signature intensity from the vehicle that the topcoat camouflage usually inhibits, making the vehicle more vulnerable to detection by the enemy (1).

Under regulation AR 750-12 (2), all U.S. Army-based ground equipment is required to have a full chemical agent resistant coating (CARC) system. The description of what typically comprises a full CARC system is defined in MIL-DTL-53072 (3). The typical CARC system consists of a conversion coating or pretreatment in direct contact with a properly prepared substrate (in this case, the high hard steel on armored vehicles), an epoxy primer in accordance with (IAW) MIL-DTL-53022 (4) or MIL-DTL-53030C (5), and the polyurethane-based topcoat IAW MIL-DTL-53039 (6) or MIL-DTL-64159B (7). A coating exception/variation was granted to Stryker manufacturers to allow the omission of the pretreatment/conversion coating step. Permission was also extended to MRAP manufacturers to omit pretreatments on that platform, allowing the primer to be directly applied to the high hard steel substrate prior to applying the topcoat. As can be seen from the photographs in figure 1, on the left is a newly received vehicle with corrosion through the paint visible on the roof. On the right is an 18-month-old vehicle showing extensive corrosion. Omission of the pretreatment/conversion coating step makes the coating process far less robust and also requires significantly more quality control diligence during coating application (8).

The original reasons that justified skipping this pretreatment/conversion coating step were: (1) the pressing needs of the Warfighter during current operations outweighed corrosion benefits; (2) hexavalent chromium-based pretreatments such as the DOD-P-15328D (9) wash primer were (and are) typically prohibited from use on new ground systems; and (3) viable alternatives, while promising in laboratory studies, had still not been demonstrated on fielded HHA-based systems such as Stryker (10), and these new technologies could not be reliably implemented in time to

meet urgent fielding requirements (11). Therefore, the Strykers and MRAPs were fielded without any pretreatment, making them more susceptible to flash rust prior to applying the primer. This creates immediate cosmetic corrosion problems and also increases the need for additional maintenance in order to prevent more serious corrosion from affecting system performance. With the continued production of more vehicles with high hard steel armor and substandard coatings, this means that corrosion will become an ever-increasing problem for these vehicles.



Figure 1. Two examples of CARC-coated MRAPs with the pretreatment step omitted.

Significant progress toward a new pretreatment was made during the execution of Strategic Environmental Research and Development Program (SERDP) Project WP-1521, *Non-Chromate/No VOC Coating Systems for DoD Applications* (12). This project, completed in fiscal year 2008, assessed a number of promising coatings and pretreatments in the laboratory by themselves and in combination, with the ultimate goal of eliminating and/or reducing volatile organic compounds (VOCs) and hexavalent chromium-based processes. The system for steel substrates consists of a pretreatment, such as trivalent chromium or a nonchromium solution applied directly to a properly prepared substrate, primed with a nonchromated primer and topcoated with a low-VOC topcoat (CARC). However, these systems will require additional demonstration on Army weapons systems before they can be considered ready for full implementation.

1.2 Objective of the Demonstration

Although the overall goal of this project is to investigate nonchromate VOC coatings for steel substrates, the objective of this demonstration plan, specifically, is to demonstrate the viability of nonchromate pretreatments as conversion coatings for HHA steel in order to improve the long-term corrosion resistance of the low-VOC CARC system and reduce lifecycle costs. The demonstration on Stryker is meant to be part of a larger demonstration that includes using identical technologies suited for use on the MRAP. Unfortunately, details of the MRAP demonstrations have not yet been established. However, the Stryker demonstrations will proceed and continue to consider the needs of the MRAP platform. The U.S. Army Research Laboratory

(ARL) will continue to work with the MRAP Program Managers Office (PMO) as well as members of the United States Marine Corp Logistics Base to identify MRAP vehicles for demonstration. When MRAP demonstration plans are finalized, an updated demo plan will be submitted to the ESTCP office. During discussions with the MRAP PMO, the project team requested an estimated start date of 2Q FY11.

As mentioned earlier, Stryker and MRAP vehicles are prohibited from using hex-chrome and are currently coated without any pretreatment or conversion coating. The products demonstrated here will satisfy the hexavalent chrome prohibition for both vehicles while minimizing environmental impact and worker safety. This demonstration is designed to generate the data necessary for authorization and implementation decisions by appropriate authorities within the DOD.

Table 1 describes the hazards targeted and components used for the demonstration on Stryker vehicles. To validate performance of the proposed coating systems, ARL was given the opportunity to use the parts of three Stryker vehicles (power entry panel [PEP] hatch, front access hatch, and side egress hatch) at the Anniston Army Depot (ANAD), AL, during an ongoing reset of the depot repair cycle float (DRCF) vehicles. These are former 1/25 Stryker Brigade Combat Team (SBCT) Stryker vehicles that will be tracked in order to determine the overall corrosion performance of the pretreatments vs. control (current) process during use in the field.

Table 1. Target hazardous material (HazMat) summary.

Target HazMat	Current Process	Applications	Current Specifications	Affected Programs	Candidate Parts and Substrates
Hexavalent chromium	Direct-to-metal prime and painting with no chemical pretreatment	Steel substrates, specifically HHA	MIL-DTL-46100E (13) TT-C-490 SSPC-SP10 MIL-DTL-53072	Stryker family of vehicles	Three access hatches on Stryker (PEP hatch, front access hatch, and side egress hatch)

1.3 Regulatory Drivers

The Occupational Safety and Health Administration (OSHA) final rules effective 30 May 2006, Federal Register No. 71: 10099-10385, states, in part, that OSHA has amended the standard limiting occupational exposure to hexavalent chromium (Cr^{6+}) (14). OSHA has determined that the current permissible exposure limit (PEL) for Cr^{6+} that workers face is a significant risk to their health. The evidence in the record for this rulemaking indicates that workers exposed to Cr^{6+} are at an increased risk of developing lung cancer. The record also indicates that occupational exposure to Cr^{6+} may result in asthma and damage to the nasal epithelia and skin. The final rule establishes an 8-h, time-weighted average exposure limit of 5 μg of Cr^{6+} per cubic meter of air (5 $\mu\text{g}/\text{m}^3$). This is a considerable reduction from the previous PEL of 1 mg per 10 m^3 of air (1 mg/10 m^3 , or 100 $\mu\text{g}/\text{m}^3$) reported as CrO_3 , which is equivalent to a limit of 52 $\mu\text{g}/\text{m}^3$ as

Cr^{6+} . The final rule also contains ancillary provisions for worker protection, such as requirements for exposure determination; preferred exposure control methods, including a compliance alternative for a small sector for which the new PEL is infeasible; respiratory protection; protective clothing and equipment; hygiene areas and practices; medical surveillance; recordkeeping; and start-up dates that include 4 years for implementing engineering controls to meet the PEL. The PEL established by this rule reduces the significant risk posed to workers by occupational exposure to Cr^{6+} to the maximum extent that is technologically and economically feasible.

In a memorandum for the secretaries for the military departments dated 8 April 2009 from the Undersecretary of Defense, signed by Mr. John J. Young Jr., a new policy is described for minimizing the use of Cr^{6+} for DOD applications (15). The memo specifically directs the military to approve the use of alternatives where they can perform adequately for the intended application and operating environment, and update relevant technical documents and specifications to authorize the use of qualified alternatives. The memo also requires Program Executive Office (PEO) or equivalent, in coordination with the military department's Corrosion Control and Prevention Executive, to certify that there is no acceptable alternative to the use of Cr^{6+} on a new system. Effectively, the memo directs DOD military departments to restrict the use of Cr^{6+} unless no cost-effective alternative with satisfactory performance is identified.

1.4 Stakeholder/End-User Issues

The process has the potential to be transitioned to any DOD facility that processes steel-based systems, as well as original equipment manufacturers (OEMs) and their subcontractors. The business case for each location will have to be completed depending on the process and coatings of interest. Benefits to the stakeholders include elimination of Cr^{6+} in the pretreatment process, reduction or elimination of VOCs during subsequent coating applications, and reduced lifecycle cost because of enhanced corrosion inhibition of the total CARC system. This demonstration plan will benefit all ground vehicles utilizing HHA steel but will initially focus on the Stryker combat vehicle. Therefore, the primary stakeholder in this case is identified as the Program Manager (PM)-SBCT.

2. Technology

The proposed alternative coatings can, in many cases, be used in place of chromated zinc phosphate. The pretreatment, or steel conversion coating in this case, is applied directly to a properly prepared, clean steel surface. The technologies being investigated include Trivalent chromium and two nonchromium coatings that are commercially available: Chemetall Oxsilan and Pittsburgh Plate Glass (PPG) Industries Zircobond 4200. Descriptions of each of the technologies to be demonstrated are described next.

2.1 Technology Description: Trivalent Chrome Pretreatment (TCP)

TCP was developed by the U.S. Naval Air Warfare Center (NAVAIR) in an effort to replace chromated sealers, post-treatments, and conversion coatings and was investigated as part of SERDP project WP-1521 (12). The majority of the information in this section is based on the findings from WP-1521. Most of the conversion coating work thus far has focused on the use of TCP on aluminum alloys. In recent years, TCP has enjoyed good success on aluminum.

However, for steel alloys and phosphated surfaces, further development is needed. One of the key advantages to using TCP is that the processing and maintenance requirements are similar to technologies used currently, thus making them favorable alternatives for depots and OEMs. This transition eliminates the need for additional training of personnel and large equipment purchases. TCP is based on a fluorozirconate complex with a trivalent chromium salt. TCP contains significantly less total chromium than the current hexavalent chromium conversion coatings and has no hexavalent chromium. The use of TCP eliminates personnel exposure to hexavalent chromium, saving labor and reporting costs associated with personal protective equipment (PPE) and worker safety regulations. Additionally, it saves time and money by eliminating the need to treat the waste stream for hexavalent chromium.

Through the prior effort just described, it was established that TCP forms a mostly zirconium oxide/fluoride, chromium oxide conversion coating on the aluminum alloy surface. Previous work has been conducted on hexavalent chromium films, suggesting a film backbone that consists of polymerized trivalent chromium hydroxide species, with a loosely hydrogen-bonded active chromate inhibitor species. Chromate films tend to be very thin over precipitates and intermetallics, only releasing the inhibitor species after the film has broken down and substrate metal is exposed. Electrochemical evidence suggests that the TCP forms a much more uniform film thickness across these intermetallic sites, with improved barrier coating properties from the denser zirconium oxide, and localized corrosion inhibition through the ability of the trivalent chromium species to bind up attacking anions, such as chloride.

Some work has been done to develop the TCP formulas for a conversion coating to be applied directly onto steel substrates. This is a novel application as there are currently no conversion coatings for steel surfaces. The initial expectation for TCP as a conversion coating on steel is to provide flash-rust inhibition for steel substrates between surface preparation and the painting process. Currently an organic-based, temporary flash rust inhibitor is applied to newly prepared steel surfaces that must be removed prior to primer application. The TCP provides a permanent surface conversion that functions to inhibit flash-rusting while promoting subsequent adhesion of organic coatings, thus eliminating the additional production step. Figure 2 shows evidence of the improved wet adhesion of an abrasive blasted substrate when treated with TCP.

One of the technologies to be demonstrated is a product manufactured by SurTec International, a TCP licensee. It is a greenish liquid with a density of 1.00–1.01 g/mL and an approximate pH of 3.8. The SurTec 650 was the TCP product tested in the ARL study funded by SERDP. In this

study, the SurTec 650 was shown to demonstrate benefits as a flash rust inhibitor as well as an adhesion promoter. Figure 3 shows the schematic of the process that will be followed for the application of the SurTec 650 on the Stryker demonstration initiated at ANAD.

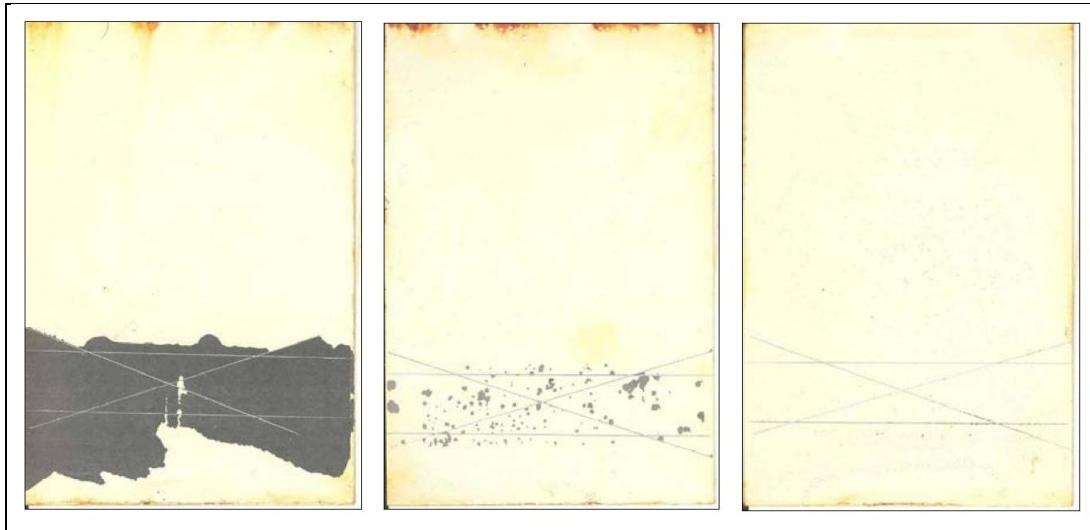


Figure 2. Results of the 7-day wet-tape-adhesion test. Acetone wipe (left), abrasive blast only (center), and abrasive blast with TCP (right), all with MIL-DTL-53022 type I primer.

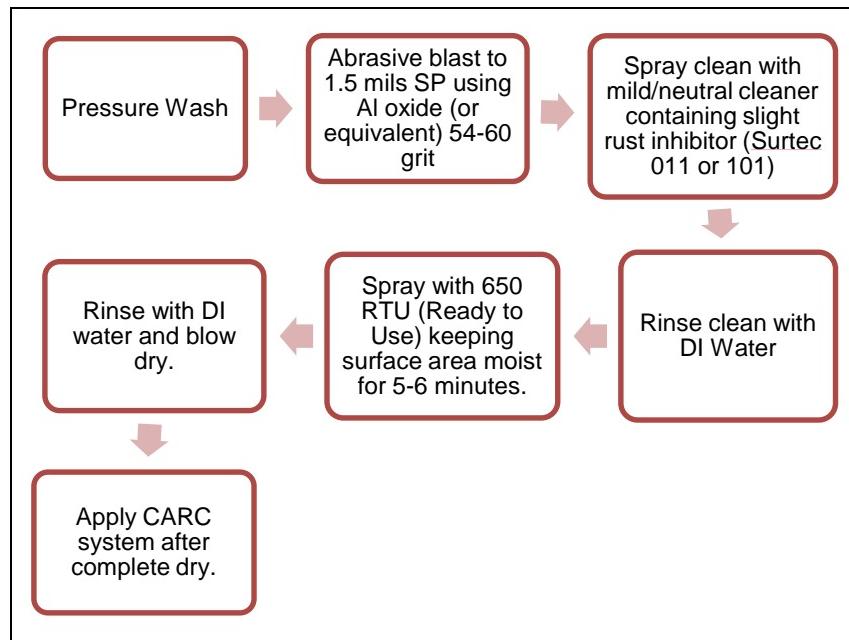


Figure 3. Schematic of the SurTec 650 TCP application process.

2.2 Technology Description: Oxsilan 9810/2

A simple silane molecule consists of a reactive silicon atom bound to an organic molecule. For paint pretreatment, however, more complex “organofunctional” silanes are often used. Careful selection of the organic constituents along the carbon backbone of the silane molecule leads to an organofunctional silane that reacts and forms bonds with both metal hydroxides on the substrate and organic groups on paint resins. These organofunctional silanes are then reacted with water during the pretreatment supplier’s manufacturing process and form what are called “polycondensates.” These retain the paint and metal-bonding properties of the silane but in an easy-to-use form. The polycondensate is the safe chemical form in which “silane” products are usually made commercially available to metal finishers.

In use, as the silane film dries on the pretreated substrate, neighboring hydroxyl groups on the silane molecule react with each other to form a dense cross-linked network. Finally, in order to further enhance performance, nonregulated group IV-B metals, such as zirconium, are used to selectively and preferentially bond to the metal substrate, providing improved corrosion resistance compared with a silane-only process. The composition of the group IV-B metals within the silane product is carefully balanced to provide the optimized deposition rate of the metal onto the substrate, which, in turn, maximizes paint performance. In effect, a dual coating is formed in one step: an inorganic coating composed of zirconium and other unregulated metals and an organofunctional silane coating. During coating dry off and/or paint cure, the silane coating cross-links to provide a durable robust coating.

The silane product to be demonstrated, Oxsilan 9810/2, is a phosphorus-free liquid, slightly acidic (pH 4-6), silane-based product that is intended to enhance the performance of organic coatings. When applied to the substrate, the Oxsilan organo-silane polymers react at room temperature with hydroxyl groups present in the metal oxide layer of a clean metal substrate to form strong covalent bonds with the metal substrate. As the film dries, neighboring hydroxyl groups react with each other to form a dense, interpenetrating, cross-linked network that is chemically bound to the metal surface (figure 4).

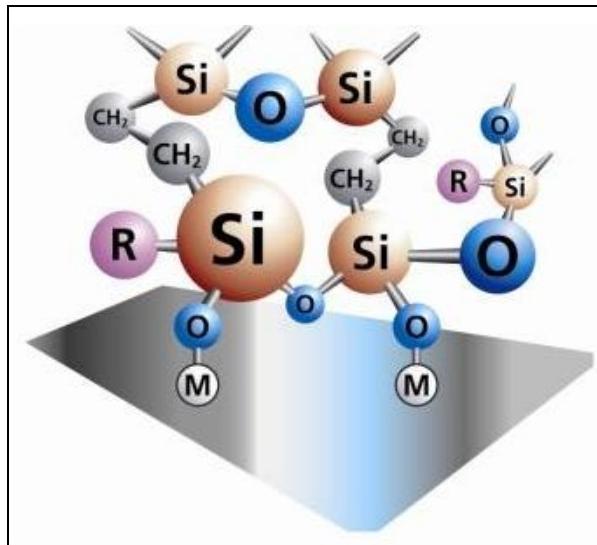


Figure 4. A schematic of the Oxsilan technology after reaction with the substrate has occurred.

Oxsilan 9810/2 is formulated for use on multiple metals, including steel, iron, aluminum, and zinc substrates. It is free of any regulated heavy metals, and is applied at ambient temperature by either spray or immersion (16). Figure 5 is a schematic of the application process that will be used on the Stryker demonstration initiated at ANAD. A dedicated pump sprayer will be used to apply all of the pretreatments (figure 6).

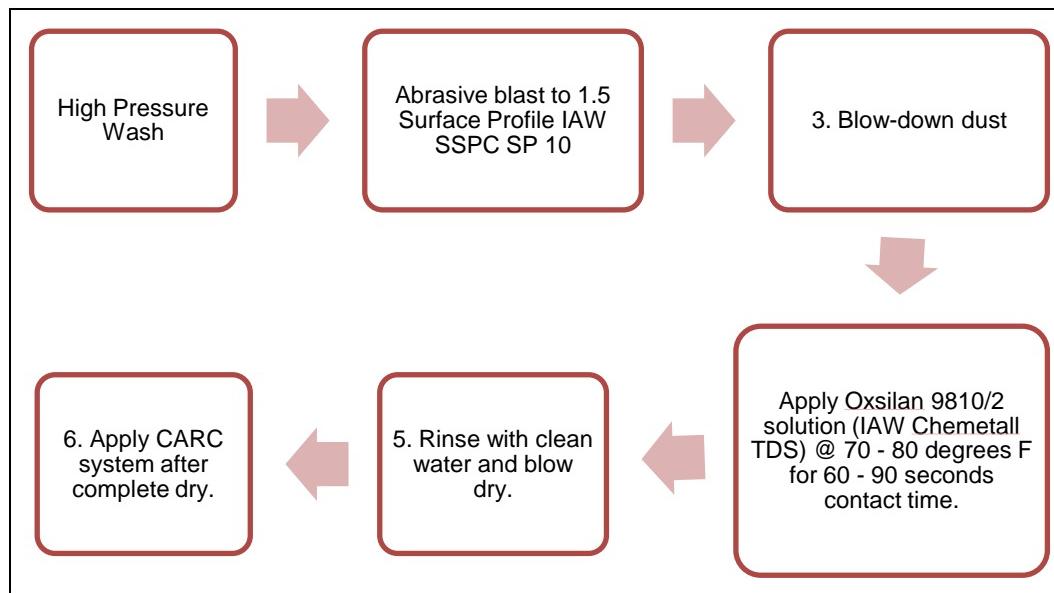


Figure 5. Schematic of the Oxsilan application process to be used on high hard steel for the Stryker demonstration.



Figure 6. A simple pressure pump sprayer is used to apply the Oxsilan, Zircobond, and the SurTec 650.

2.3 Technology Description: Zircobond 4200

PPG has developed Zircobond 4200 pretreatment, an alternative pretreatment based on zirconium chemistry and a proprietary blend of additives. Zircobond 4200 pretreatment reduces the sludge by-product from the pretreatment process by at least 80% compared to zinc-phosphate-based products, and it can be used as a drop-in replacement in existing pretreatment lines. The Zircobond 4200 system is formulated to provide corrosion resistance for steel, galvanized steel, and aluminum substrates. It is a clear, light blue liquid with a specific gravity of 1.104 and has a diluted working pH of 4.0 and 5.0. This product can be applied by both immersion or spraying. The procedure for the spray application used is shown in figure 7.

3. Technology Development

The primary motivation for this project is the promise of transitioning the success of the TCP technology to steel. Trivalent chrome pretreatments were studied for use on steel substrates as part of the SERDP project WP-1521. Trivalent chromium compositions and processes were originally developed as a chromate conversion coating alternative for aluminum alloys, and the vast majority of research has been focused on nonferrous applications.

Dr. Vinod Agarwala is the original inventor of the TCP technology. In 1994, he studied the electrochemical impedance of trivalent chrome pretreatments on aluminum. The results showed a 10–100 fold increase in the polarization resistance of the surface films compared with the untreated aluminum alloy. These electrochemical results compared well with the corrosion behavior in B117 salt fog testing. The trivalent chromium-treated surfaces showed no corrosion for up to 200 h in 5% salt spray. A post-treatment with an oxidizer even further raised the coating's resistance due to improved corrosion protection (17).

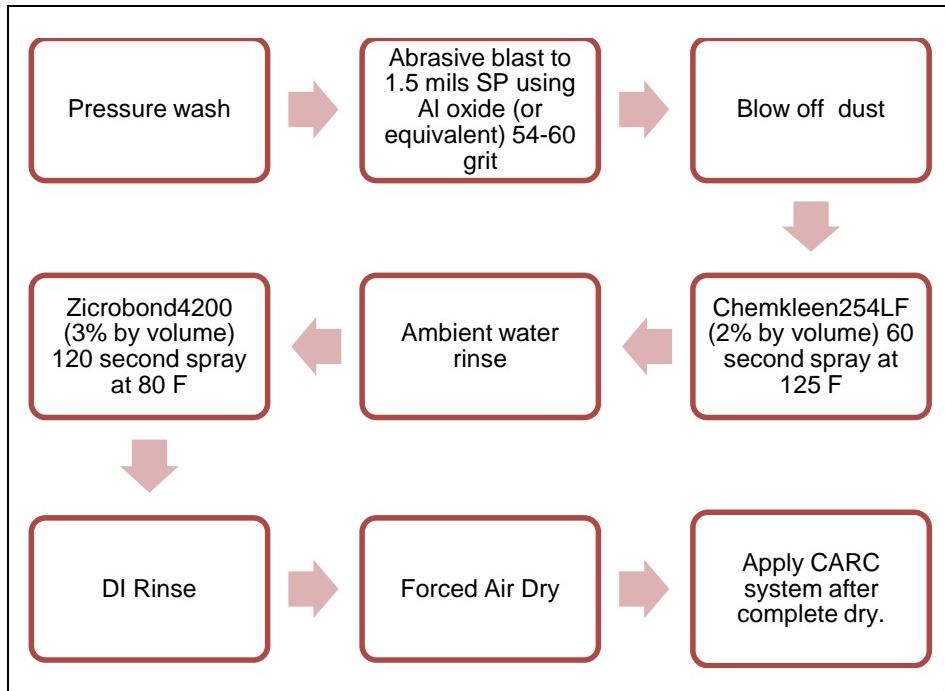


Figure 7. Schematic of the PPG Zircobond 4200 application process used on high hard steel for the Stryker demonstration.

A modified version of the trivalent chrome was later developed by the U.S. Naval Air Systems Command (NAVAIR), Patuxent River, MD. Among the inventors were Dr. Michael Kane and Craig Matzdorf, who conducted a demonstration of the technology on the aft section of two S-3 U.S. Navy aircraft using a spray on process at the Naval Aviation Depot, North Island, CA. The report included toxicology information consistent with what is presently stated in the current materials safety data sheets (MSDSs). Results of the demonstration were not available at the time of their report (18).

Trivalent Chrome Process (TCP) as a Sealer for MIL-DTL-8625F Type II, IIB, and IC Anodic Coatings (19) documents the evaluations of TCP as sealers for various anodic coatings conducted by Materials Engineering, Naval Air Warfare Center Aircraft Division (NAWCAD), Patuxent River. The performance of TCP as a sealer was compared with standard sealers like dichromate and water, which are commonly used in aerospace and other industries. Paint adhesion was performed with commonly used high solids and water-borne chromated and chromate-free primers qualified to MIL-PRF-23377 (20) and MIL-PRF-85582 (21). In these evaluations, TCP performs as good as or better than chromate in corrosion resistance and equal to chromate in paint adhesion. TCP is far superior to hot water for sealing. An additional benefit is that the TCP is applied at ambient conditions for 5–10 min. Chromate and water sealers are applied at 190–200 °F for up to 25 min (19).

Many other studies have been conducted by ARL to validate the performance of TCP on various aluminum substrates. One such study focused on aluminum alloy 5059-H131 (22) under different surface treatment conditions. The surface treatment conditions included abrasively blasted, with and without a commercial trivalent chrome pretreatment (TCP). Corrosion resistance was evaluated using GM 9540P (23) and ASTM B 117 (24) neutral salt fog methods. Adhesion was assessed using dry pull-off (ASTM D 4541 [25]) and wet pull-off adhesions (ASTM D 3359A [26]). TCP showed excellent performance and was recommended as the pretreatment of choice based upon its qualification with the conversion coating MIL-DTL-5541 (27) and MIL-DTL-81706 (28) and its ability to sustain performance under bare conditions (29).

In recent years, TCP has been considered for use in ferrous and multimetal applications. However, more research on steels is necessary to understand the mechanism of corrosion mitigation in detail. A logical application of TCP for steel would be its use as a zinc phosphate sealer. NAVAIR Indian Head Division qualified TCP as an alternative to hex-chrome sealers for propellant and cartridge actuated devices. TCP was qualified to replace the hexavalent chromate conversion coating on zinc-nickel plated steel. Unpainted test panels exhibited at least 42 days of resistance to cyclic salt fog. These panels lasted at least 4 days when subjected to cyclic sulfur dioxide and cyclic salt fog testing, with full red rust evident on the seventh day. Painted and scribed TCP panels previously subjected to 10 days of humidity and 120 days of salt cyclic fog were subject to 78 days of cyclic sulfur dioxide and salt fog; paint was still largely intact, with only moderate scribe corrosion and paint blistering near the scribe (30).

Although the primary thrust of this demonstration is to evaluate the feasibility of trivalent chrome pretreatment for steel substrates, it would not be prudent to ignore the potential of other commercial off-the-shelf pretreatments for steel and compare their performance to TCP. For this reason, two commercial available products will be evaluated: Chemetall Oxsilan and PPG Zircobond 4200.

4. Advantages and Limitations of the Technology

In this section, the advantages and limitations of the demonstrated technology are listed as compared to the painting process currently employed on the Stryker vehicles. The primary material used in the construction of these platforms is MIL-DTL-46100E HHA steel, with a hardness in excess of 50Rc. The material hardness, coupled with the possible existence of residual stresses induced during manufacturing, make this material susceptible to stress corrosion cracking (SCC) under certain conditions. Therefore, because of SCC concerns associated with some pretreatments, such as phosphate and wash primer, these platforms are painted without the benefits of a pretreatment. The current processes for both platforms are described in section 4.2 of this demonstration plan. Only a flash rust inhibitor is used; overall, the application processes

of the alternative technologies to be demonstrated are very similar to the current process. For simplification, the advantages of each product demonstrated will be compared to the current product used on Stryker—Cheminhib 420.

4.1 SurTec 650 (TCP)

Advantages (Technical):

- Is proven effective as a conversion coating on aluminum.
- The addition of a true chemical pretreatment/conversion coating will provide a complete CARC system as defined in MIL-DTL-53072 for armor steel platforms.
- Adds another layer of corrosion protection while improving coating adhesion.
- Added flash rust inhibition.
- Easy to apply, drop in replacement.
- Low process risk of stress corrosion cracking.
- Provides a more robust process that will protect against deficiencies in the inorganic coating process.

Advantages (Safety and Environmental):

- No hexavalent chromium.
- Not irritating to the skin or eyes.

Limitations:

- Little historical data for use on steel.
- No color change to substrate surface to indicate full coverage.

4.2 Chemetall Oxsilan (Silane)

Advantages (Technical):

- Has a history of improving coating adhesion on steel.
- The addition of a true chemical pretreatment/conversion coating will provide a complete CARC system as defined in MIL-DTL-53072 for armor steel platforms.
- Improves performance of organic coatings by providing better adhesion of the primer.
- Easy to apply, drop in replacement.
- Offers a low process risk of stress corrosion cracking.

Advantages (Safety and Environmental):

- No hexavalent chromium.

Limitations:

- Requires some personal protection equipment.
- Not designed to provide uncoated corrosion protection or flash rust inhibition.
- No color change to substrate surface, making full coverage difficult to detect.

4.3 PPG Zircobond 4200

Advantages (Technical):

- The addition of a true chemical pretreatment/conversion coating will provide a complete CARC system as defined in MIL-DTL-53072 for armor steel platforms.
- Improves performance of organic coatings by providing better adhesion of the primer.
- Easy to apply, drop in replacement.
- Low process risk of stress corrosion cracking.

Advantages (Safety and Environmental):

- No hexavalent chromium.

Limitations:

- Not as robust as others; product is more sensitive to process conditions.

5. Performance Objectives

The performance objectives with acceptance criteria for the demonstrated technologies will be evaluated in accordance with the tests delineated in the joint test protocol (JTP) provided in appendix A. The functional performance objectives are summarized in table 2. The primary material used in the construction of these platforms is MIL-DTL-46100E HHA steel.

Performance objectives will be achieved using HHA as the base metal. The existing direct-to-metal process currently used on Stryker is considered the baseline process. The hardness of HHA is typically in excess of 50Rc. This hardness, coupled with the possible existence of residual stresses induced during manufacturing and coupled with aggressive environments, can make this material susceptible to EAC. For this reason, the fracture toughness in a corrosive environment (K_{1eac}) will be evaluated.

Table 2. Performance objectives for alternative pretreatments.

Performance Objective	Data Requirements	Success Criteria
Adhesion test	ASTM 4541 pull-off adhesion	Minimum average 30 events rating of 1200 lb/in ² on 1.5-mil profile surface
	ASTM D 3359 dry adhesion	Adhesion rating (steel) >4B; adhesion rating
	ASTM D 3359 wet adhesion	Scribed area rating (steel) ≥3A after 24 h at ambient
Hydrogen embrittlement	ASTM E 399-97	No detrimental effect to K1c of substrate. High hard K1c at 48-51Rc shall maintain K1eac ≥19 (ksi/in)
Chip resistance	SAE-J400	After one cycle, chip rating NLT 6B for steel
Accelerated corrosion	ASTM B 117 salt fog	After 500 h of exposure: steel substrate rating ≥7 scribed
	GM 9540P (GMW14872) cyclic corrosion ASTM D 1654	After 80 cycles: steel substrate rating ≥5 scribed and ≥6F unscribed
Humidity testing	Comparative test for flash rust inhibition	No flash rust after 24 h of exposure to ambient temperature and 60% relative humidity
Outdoor exposure	Tropical climate exposure at Kennedy Space Center outdoor site ASTM D 1654 ASTM G 50	Three years of exposure: specimen has a minimum of 25% less creepage from scribe than current corrosion protection system
Toxicity clearance	Toxicity clearances and full disclosure from CHPPM	Approved by processing facility
Processing time	TT-C-490	Equivalent or less than existing process
Field testing	TT-C-490	Equivalent or less than existing process
Ease of use	Feedback from field technician on usability of technology and time required during demonstration	No operator training required

6. Sites/Platform Description

6.1 Test Platforms/Facilities

There are two parts to this demonstration of pretreatments for HHA steel. The first will take place at ANAD during an ongoing reset of Stryker DRFC vehicles. This reset presented ARL with a window of opportunity to use some major components on actual Stryker combat vehicles (figure 8) to validate the performance of the candidate pretreatments. SBCT has agreed to allow ARL to demonstrate the pretreatments on the hatches of three Stryker vehicles (PEP, front-access, and side-egress hatches). The reset of these vehicles is set to end on or about 15 October 2010.



Figure 8. Stryker combat vehicle similar to those being reset at ANAD.

The Anniston site was selected for three reasons: (1) it was the location performing the reset on a major combat vehicle constructed of high hard steel; (2) PMO SBCT and ARL have a written memorandum of agreement for environmental compliance, enhanced materials, advanced coatings, improved processes at OEM and depot facilities; and (3) through the Sustainable Painting Operations for Total Army program, ARL has enjoyed a long-standing, productive working relationship with ANAD to eliminate methylene chloride in the depainting operations at ANAD. These factors will provide the program with the best chance for success. All of the necessary work will be performed on-site at ANAD. The parts (hatches) will be removed from each vehicle by the Stryker reset team and tagged in order to stay mated with their specific vehicles. Then the hatches will be transported by ARL personnel to ANAD Department of Engineering Quality production area to be abrasive blasted, pretreated, primed, and painted. ARL will return the parts to the Stryker reset reinstallation. All of this will be documented in order to track each part and vehicle in the field for periodic inspections.

The pictures in figure 9 are the actual vehicles used for the demonstration. The picture on the left shows two of the hatches—the larger side egress door and smaller power entry panel located on the left side of the vehicle. The photo on the right is the front access panel located on the front of the vehicle.



Figure 9. One of the actual Stryker vehicles and hatches used in the demonstration.

6.2 Present Operations

As mentioned in the Introduction, a true CARC system, as defined in MIL-DTL-53072, consists of a three-part process: a conversion coating or pretreatment in direct contact with a properly prepared substrate, followed by an epoxy primer, and then a polyurethane-based topcoat. A coating exception/variation was granted to Stryker and MRAP manufacturers to allow the omission of the pretreatment/conversion coating step, which necessitates the primer to be directly applied to the high hard steel substrate prior to topcoating. Figures 10 and 11 are flow diagrams for the painting process for Stryker and MRAP, respectively. Note that there are interim steps in both cases that involve applying a flash rust suppressor, which is a temporary corrosion inhibitor and not meant to assist in the long-term corrosion protection or adhesion of the CARC system.

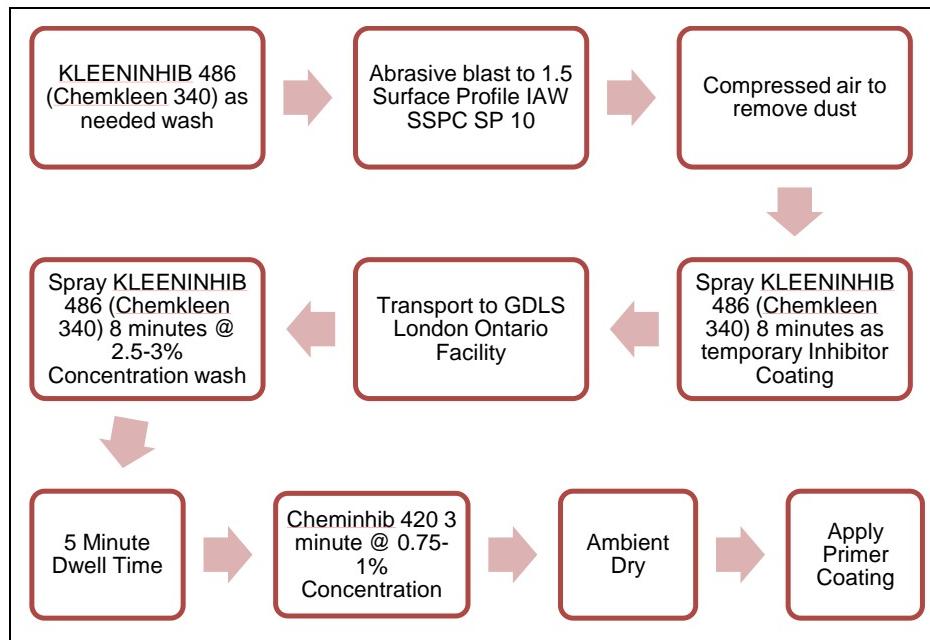


Figure 10. Typical flow diagram of the current painting process for Stryker vehicles.

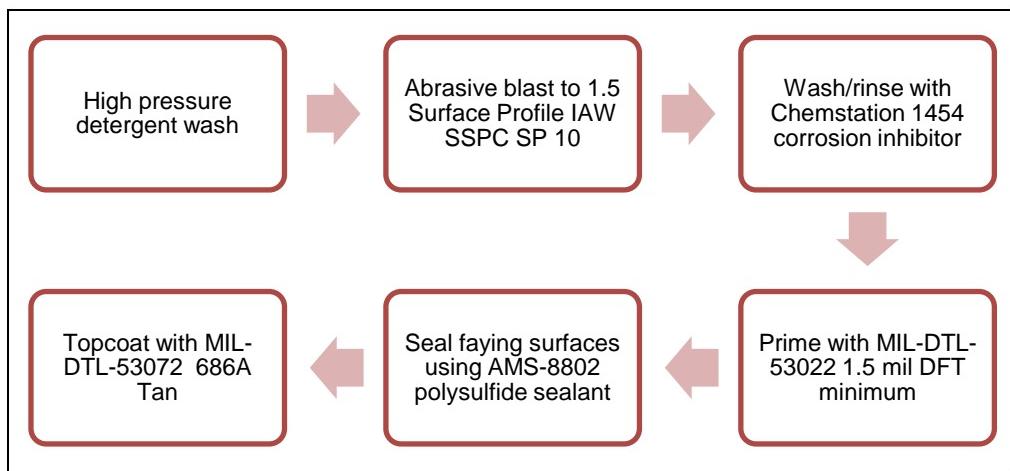


Figure 11. Typical flow diagram of the current painting process for MRAP vehicles.

The demonstrated technology is intended to replace the temporary flash rust suppressor step in the process and, thus, will not require additional steps to the current process. In fact, in some cases, it is expected to save time overall. Moreover, the demonstrated technology is expected to provide additional corrosion protection for the CARC system.

6.3 Site-Related Permits and Regulations

Additional site-related permits or regulations are not anticipated for the demonstration to be conducted at ANAD. The facility has had the capability to process and apply pretreatments, including hexavalent chrome pretreatments, and holds the necessary documentation to perform the demonstrated chemical pretreatments and dispose of any waste if necessary.

7. Test Design

7.1 Conceptual Experimental Design

The details of the laboratory testing are provided in the JTP (appendix A). Although significant testing and evaluation of trivalent chrome pretreatments (SurTec 650) on steel substrates was performed as part of the SERDP project WP-1521, MIL-DTL-46100 HHA steel substrates were not part of the matrix. For this reason, it is crucial to evaluate SurTec 650 vs. two other commercially available alternative steel conversion coatings (pretreatments) on HHA steel. The three pretreatments, SurTec 650 TCP, Chemetall Oxsilan (Silane), and PPG Zircobond 4200 (ZrOx), will be laboratory validated and field tested on HHA test panels according to the JTP provided in appendix A. In addition to the laboratory validation described in the JTP, field testing on Stryker will be initiated at the ANAD and will proceed according to the schedule in figure 12.

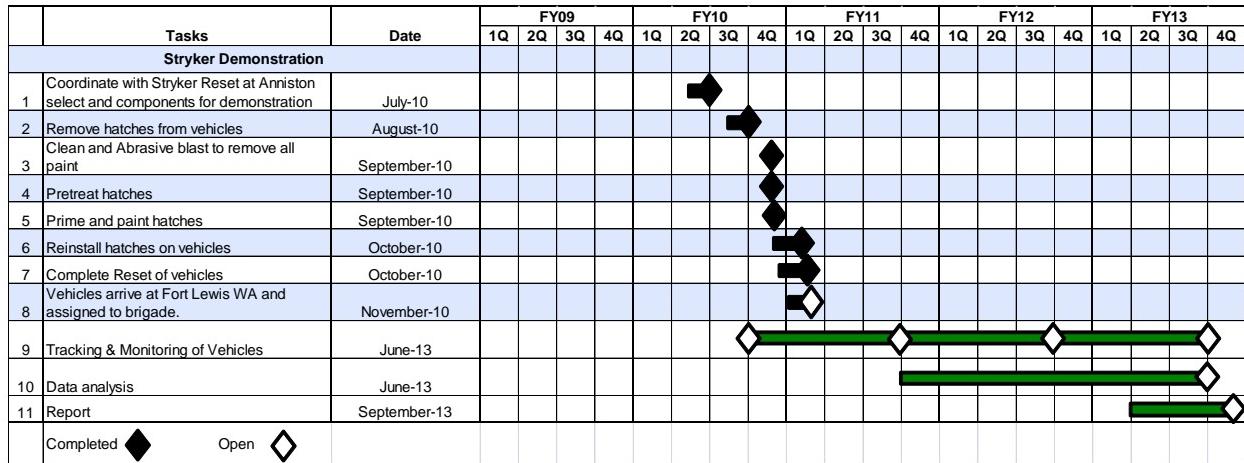


Figure 12. Gantt chart for the demonstrations on the Stryker access hatches.

All of the chemicals for the demonstration were provided by the manufacturers, along with specific instructions on the application process. These can be seen in the process flow diagrams in section 2.

7.2 Predemonstration Testing and Analyses

Some of the initial testing is described in section 3. However, to fully evaluate the steel conversion coatings on armor steel, initial screening tests were performed to gage the relative performance of the alternatives vs. the baseline or currently used process. Because of the very small window of opportunity for access to vehicles during the reset of the former 1/25 SBCT vehicles (DRCF), a full battery of tests could not be completed prior to initiating the demonstration. Adhesion and ASTM B117 neutral salt testing was performed and compared to the current treatment. Table 3 lists the acceptance criteria for screening the candidate pretreatments.

Table 3. Screening requirements for demonstrations on Stryker.

Test	Acceptance Criteria	Test Method References
Adhesion (pull-off)	Meets or exceeds adhesion strength of DOD-P-15328D on similarly prepared abrasive-blasted surface of 1.5-mil profile or 1200 lb/in ²	ASTM 4541 pull-off adhesion
Corrosion resistance (neutral salt spray [fog])	After 336 h of exposure: Steel substrate rating ≥ 7 scribed	ASTM B 117 ASTM D 1654
Toxicity clearances	Obtain toxicity clearances and site approval	None

The adhesion of the primer and topcoat to the substrate as enhanced by the pretreatments is an important consideration. The demonstrated technology must exhibit adhesion greater than or equal to that of wash primer DOD-P-15328D (9). Figure 13 gives the average adhesion values for all pretreatments. The three conversion coatings demonstrated, Surtec 650, Oxsilan 9810/2, and Zircobond 4200, were all within the acceptance criteria for adhesion.

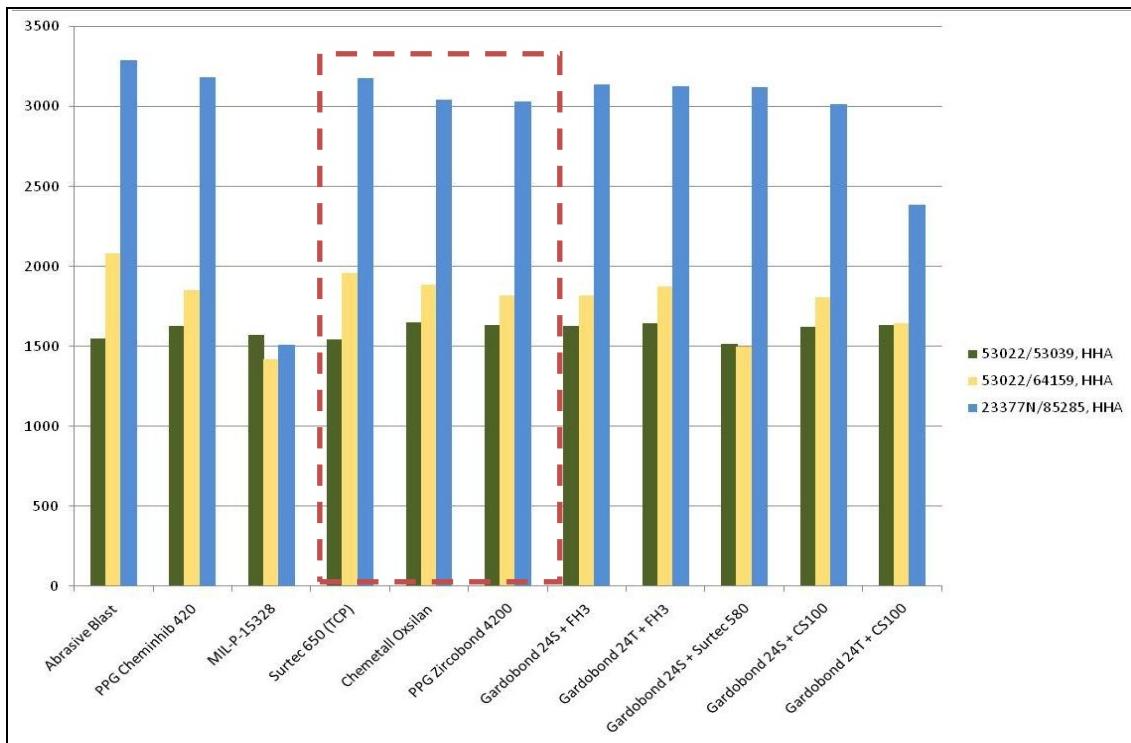


Figure 13. Pull-off adhesion strength for all pretreatments on abrasive-blasted HHA.

All of the pretreatments were screened for corrosion resistance using ASTM B 117 neutral salt fog testing. A representative of each of the three demonstrated technologies is compared with the current technology (PPG Cheminhib 420) in figures 14 and 15. All of the panels shown passed the screening test with a rating of 7 or above (31) for scribed panels after 336 h of salt fog exposure. The results of the B117 ratings on pretreated panels coated with MIL-C-53022/MIL-PRF-53039 are shown in figure 15.

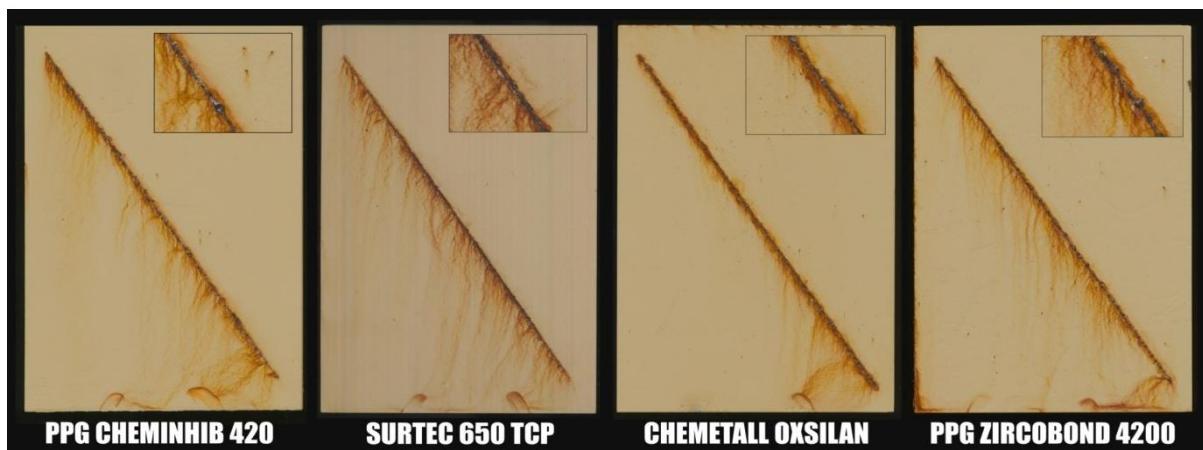


Figure 14. MIL-C-53022/MIL-PRF-53039 on abrasive-blasted HHA at 336 h B117.

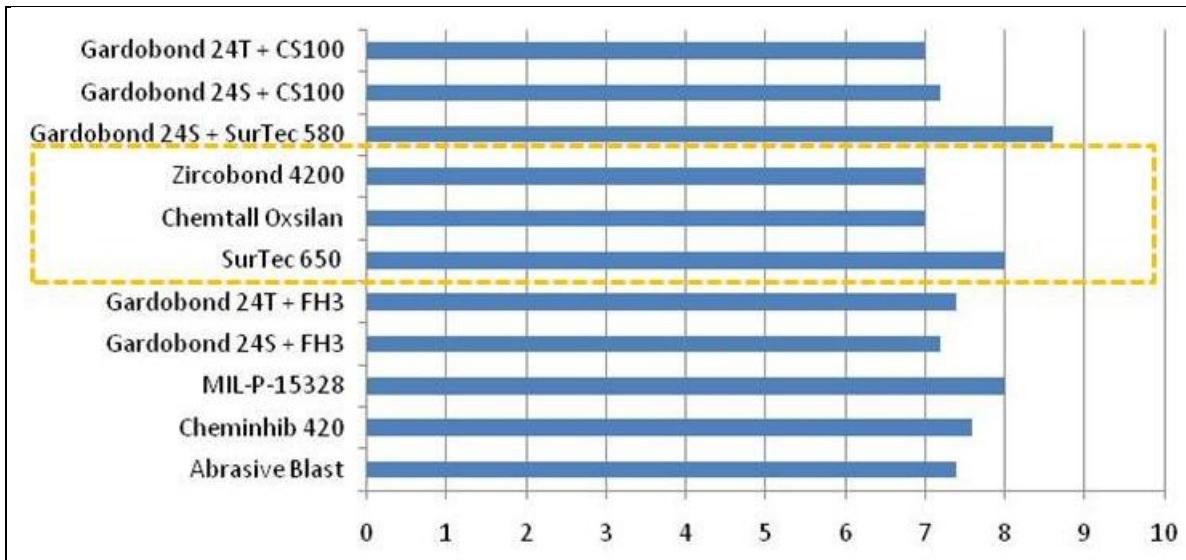


Figure 15. ASTM D 1654 ratings for scribed HHA panels after screening of 336 h B117.

Conversion coatings were selected for this demonstration because of the reluctance to phosphate HHA steel and because the process for these conversion coatings is similar to the process used for the PPG Cheminhib 420. The three candidates, if approved, would essentially be a drop-in replacement for the current technology.

7.3 Design and Layout of Technology Components

7.3.1 Stryker Components

7.3.1.1 Abrasive Blasting

All hatches are first pressure-washed to remove dirt, grease, and grime prior to abrasive blasting. The hatches are then abrasive-blasted to a surface profile of 1.5 mil in accordance with Steel Structures Painting Council (SSPC) standards.

7.3.1.2 Surface Cleanliness

Visual cleanliness is determined using SSPC VIS1, Standard for Abrasive Blasting. A water break test is performed to determine the presence of any contaminants prior to pretreatment.

Each of the candidate conversion coatings will be applied to major components of each platform according to the manufacturer's required procedure described in section 5. Figure 16 is a photograph of some of the parts being treated.



Figure 16. Actual application of the steel conversion coating on high hard Stryker hatches.

Once pretreated, all of the hatches were stored overnight for 19 h in ambient shop conditions (60%–70% relative humidity) to duplicate actual coating process lines and evaluate flash rust inhibition. Figure 17 shows an example of one hatch immediately after the application of the conversion coatings. The pictures show the hatch immediately after pretreatment (left) and after approximately 19 h of ambient indoor exposure (right). Only the Zircobond showed a significant discoloration of the steel. The surface changed from a homogeneous clean gray steel color to a surface with gold- and rose-colored blotches, seen in figure 17. The color change appeared almost immediately after applying the product. It was not clear whether it was flash rust or a result of a reaction of the Zircobond and the steel. The Oxsilan and SurTec 650 showed no significant discoloration. Only a slight darkening of the gray metal was observed with these two pretreatments.

According to section 3.5.5 of TT-C-490 (32), the organic coating shall be applied to thoroughly dried surfaces within 24 h after pretreatment. All hatches were primed within 23 h of pretreatment and topcoated the following morning (20 h later). After the hatches were painted, they were all returned to the Stryker Reset Team to be reinstalled on their respective vehicles. Table 4 lists the actual vehicle identifications and the pretreatments used for each hatch on the vehicles.



Figure 17. Front access hatch pretreated with PPG Zircobond 4200 immediately after pretreatment (left) and after approximately 19 h of ambient indoor exposure (right).

Table 4. Conversion coatings used to treat specific components.

Component	Stryker Demonstration Vehicles Identification		
	MEV-76	MGS-25	ICV-382
PEP hatch	SurTec 650 (TCP)	PPG Zircobond 4200	Chemetall Oxsilan
Front access hatch	PPG Zircobond 4200	Chemetall Oxsilan	SurTec 650 (TCP)
Side egress hatch	Chemetall Oxsilan	SurTec 650 (TCP)	PPG Zircobond 4200

7.4 Field Testing

The Stryker demonstrations were coordinated through the Stryker PMO. Permission was granted to ARL to discuss opportunities for demonstration candidate pretreatments with the Stryker Reset Team at ANAD. The pace of this reset would provide ARL with more opportunities because it was conducted slower than the other resets. ARL met with Mr. James Swann at Anniston on 11 August 2010 to discuss available opportunities. Mr. Swann suggested that the hatches described in section 1.2 were not likely to be changed out because each was fitted to the vehicle. Once the demonstration vehicles and parts were identified, the following steps for the Stryker demonstrations were carried out:

1. Screen pretreatments for minimum performance using criteria in table 3.
2. Acquire pretreatment chemicals and accompanying MSDSs, toxicity clearances, and gain site approval for processing parts.
3. All hatched are abrasive-blasted to bare metal, as seen in figure 18, and pretreated according to the manufacturer's recommended guidance outlined in section 2.



Figure 18. All hatches shown here are abrasive-blasted and prior to pretreatment and paint.

4. Once hatches are reinstalled, ARL will track vehicle location for subsequent inspections. Currently, these vehicles have been designated for Joint Base Lewis-McChord, Fort Lewis, WA. Our point of contact will be:

Catherine Doherty
catherine.doherty@us.army.mil
Office: 586-282-2157
DSN: 782-2157, BB: 586-770-8721

Inspection intervals are shown in task 9 of figure 12. ARL or a contracted representative will inspect each vehicle at the predetermined inspection time. However, this will depend on the location of each vehicle and the ability to gain access to each for inspections.

7.5 Performance Assessment Plan

7.5.1 Laboratory Validation

All of the candidate steel conversion coatings will undergo a comprehensive evaluation as determined by the JTP provided in appendix A. The target substrate material for this demonstration is MIL-DTL-46100 HHA steel; therefore, all tests will be validated on test panels of this material. Table 2 represents an overview of the performance requirements of the technology being demonstrated.

7.5.2 Quality Control

For the initial demonstration of the Stryker components, no major capital investment was necessary. Only an approved suitable location to apply the candidate pretreatments was needed, and miscellaneous supplies and spray equipment were purchased. The manufacturers were consulted in order to obtain their recommended specifications for the application of their

products. Step-by-step instructions were supplied to ARL prior to initiating the demonstration. These specifications were used to control the application process. A person with a stopwatch was designated to monitor the required time intervals. Deionized (DI) water was used in all steps of the process except the pressure-washing of the parts. Notes were taken throughout the process. Test panels were also conversion-coated with the same products by the same applicator for later laboratory testing at ARL. Figure 19 shows the applicator and hatches during the pretreatment process. The applicator is force air drying the parts after the required rinse. Humidity, adhesion, and ASTM B117 salt fog tests will be performed at ARL on these panels to ensure that they meet the criteria just stated. The application instructions for each are given.



Figure 19. Applicator showing forced air drying parts with shop air.

7.5.2.1 SurTec 650 TCP (Ready to Use [RTU]).

1. Pressure-wash all parts to remove dirt and grime.
2. Abrasive-blast to 1.5-mil surface profile using Al oxide (or equivalent) 54–60 grit.
3. Spray clean with mild/neutral cleaner containing slight rust inhibitor (Surtec 011 or 101).
4. Rinse clean with DI water.
5. Spray with SurTec 650 RTU, keeping surface area moist for 5–6 min.
6. Rinse with DI water and blow dry.
7. Apply CARC system after complete dry.

7.5.2.2 Chemetall Oxsilan

1. Pressure-wash all parts to remove dirt and grime.

2. Abrasive-blast to 1.5 surface profile IAW SSPC SP 10.
3. Blow down dust.
4. Apply Oxsilan 9810/2 solution (IAW Chemetall TDS) at 70–80 °F for 60–90 s contact time.
5. Rinse clean with DI water and blow dry.
6. Apply CARC system after complete dry.

7.5.2.3 PPG Zircobond 4200

1. Pressure-wash all parts to remove dirt and grime.
2. Abrasive-blast to 1.5 mil SP using Al oxide (or equivalent) 54–60 grit.
3. Blow off dust.
4. Chemkleen 254LF (2% by volume) 60 s spray at 125 °F.
5. Ambient DI water rinse.
6. Apply Zircobond 4200 (3% by volume) 120 s spray at 80 °F.
7. DI rinse.
8. Forced air dry.
9. Apply CARC system after complete dry.

7.5.3 Performance Validation on Stryker Parts

The methods for validating the overall performance of the demonstrated technology on Stryker components are summarized in table 5. As discussed earlier, the metrics for evaluating the candidate pretreatments are contained in the JTP. Depending on the accessibility of each vehicle, periodic inspections will be completed during the field testing. Only the hatches identified earlier were treated and installed on the specific vehicles. The metric for evaluating the hatches during periodic inspections will be a visual comparison with the base vehicle using the Society for Protective Coatings SSPC-VIS-2 *Standard Method for Evaluating the Degree of Rusting on Painted Steel Surfaces* (33). The success criteria for the fielded hatches will be performances greater than or equal to the base vehicle (baseline). The exact area of comparison on the base vehicle will be recorded at the time of the inspections.

Table 5. Validation methods and expected performance metrics.

Performance Criteria	Expected Performance Metric (Pre-Demonstration)	Performance Evaluation Method
Primary Performance Criteria		
Product testing	The performance of the alternative technology will meet or exceed the current process employed on Stryker during manufacturing, as defined in the JTP in appendix A.	Laboratory analysis and field testing
Hazardous materials	Maintains a hex chrome-free platform.	Assessment of product constituents and previous studies
Hazardous waste	Meets or exceeds current process used in Stryker manufacturing.	Operating experience and assessments
Factors affecting technology performance	Compare alternatives in identical operating conditions.	Operating experience
Secondary Performance Criteria		
Ease of use	Man hours and training shall be equivalent to current process used in Stryker manufacturing.	Operating experience
Maintenance	Requirements for record-keeping for storage and clean up shall be equivalent to current process.	Compare records
Scale-up capability	Identify additional equipment, if any, necessary to scale up process for full vehicle treatment.	Operating experience and investigation

8. Cost Assessment

A cost assessment was performed for this project as it related to MRAP, but it is believed that the assumptions made will apply to Stryker. Stryker and MRAP are similar-sized vehicles, and both are constructed mainly with HHA steel.

The work time required to prepare and paint an MRAP is approximately 16 h. This includes abrasive blasting, pressure washing, prepping, and painting. The disassembly steps needed prior to surface coating tasks (breakdown, etc.) take several times that. Based upon a conversation with an OEM source, a conservative 5:1 ratio of disassembly hours to painting hours exists. Therefore, the total cost to disassemble or “breakdown” for hull strip and painting operations is conservatively estimated to be five times the number of hours as the actual surface prepping and painting stages. When totaled, the work hours add up to approximately 96 h per vehicle at a cost of \$13,440. The total paint used is estimated to be 4.9 gal of MIL-DTL-53022 primer at cost of \$56.00/gal and 5 gal of MIL-DTL-53039 topcoat at a cost of \$50.52/gal, resulting in a total cost of paint of \$527.00 per vehicle. The total cost for repainting an MRAP is calculated at \$13,967.00.

The preparation steps and associated costs, such as labor, will all remain as stated to implement any of the pretreatments. A modest additional cost per vehicle will be added as a result of the pretreatment step, although, as mentioned earlier, a flash rust inhibitor step exists in the current process. Therefore, this assumption is considered conservative. Taking into account complex shapes and geometries, a conservative estimated surface area for an MRAP vehicle is 1000 ft². For spray zinc phosphate treatments, the cost per 100 ft² is \$2.00 (\$20.00 per vehicle). The TCP chemical treatment is even less costly at approximately \$0.50 per 100 ft² (\$5.00 per vehicle). Only chemical conversion coatings are being demonstrated on Stryker. As stated earlier, Stryker is currently using no pretreatment in their CARC system. Therefore, the pretreatment over the estimated 100 ft² is the only additional cost.

The current coating system used for MRAPs has shown obvious deficiencies and will likely need to be completely repainted an average of every 3 years if the current processes remain in place. If improved coating systems are fully utilized from this demonstration, it is expected that the repaint interval will increase by a factor of 2. For the chart in figure 20, using the current coating system, the entire fleet of 15,500 will require repainting every 3 years. This schedule assumes that a third of the fleet will be repainted every year to maintain a consistent processing cycle. By implementing the new system, the repaint cycle will double, thereby reducing the annual recoating costs by 50%. This reduction means that beginning after year 4, only one-sixth of the MRAP fleet will need to be repainted, at a cost of \$14,692/vehicle.

Figure 20 shows only the costs and savings associated with complete repainting of each vehicle. (Note that no savings or benefits are realized until year 4.) Based on the assumption that the initial painting of 15,500 vehicles with the enhanced (longer service life) coating requires repainting of only one-sixth of the fleet after year 4, the 50% reduction in “New System Costs (column D) only occurs during year 4. Additional benefits from using the enhanced (longer service life) coating include reduced unit level corrosion maintenance efforts as well as benefits to other platforms. These additional benefits are not quantified here but would likely be substantial.

				Investment Required			1,500,000
				Return on Investment Ratio	132.43	Percent	13243%
				Net Present Value of Costs and Benefits/Savings	308,185,811	506,828,441	198,642,630
A Future Year	B Baseline Costs	C Baseline Benefits/Savings	D New System Costs	E New System Benefits/Savings	F Present Value of Costs	G Present Value of Savings	H Total Present Value
1	72,162,833					67,443,384	67,443,384
2	72,162,833		72,162,833		63,027,018	63,027,018	
3	72,162,833		72,162,833		58,906,521	58,906,521	
4	72,162,833		72,162,833		55,053,025	55,053,025	
5	72,162,833	36,081,417			25,726,050	51,452,100	25,726,050
6	72,162,833	36,081,417			24,041,048	48,082,096	24,041,048
7	72,162,833	36,081,417			22,467,898	44,935,796	22,467,898
8	72,162,833	36,081,417			20,999,384	41,998,769	20,999,384
9	72,162,833	36,081,417			19,624,682	39,249,365	19,624,682
10	72,162,833	36,081,417			18,340,184	36,680,368	18,340,184

Figure 20. Return on investment calculation of demonstrated technology on MRAP.

The demonstration on Stryker is meant to be part of a larger demonstration that will include the same technologies demonstrated on MRAPs. Unfortunately, the details of the MRAP demonstrations have not yet been established. As can be seen by the cost assessment, a substantial amount of time and effort has gone into considering the needs of the MRAP platform. ARL will continue to work with the MRAP PMO as well as members of the U.S. Marine Corps Logistics Base to identify MRAP vehicles for demonstration. At that time, an updated demonstration plan will be provided to the Environmental Security Technology Certification Program (ESTCP) and a full cost benefit analysis will be performed by the National Defense Center for Energy and Environment (NDCEE). The NDCEE will employ the Environmental Cost Analysis Methodology (ECAM). ECAM meets ESTCP requirements and is a consistent methodology to quantify and evaluate costs and benefits of technology investments more accurately than traditional approaches. It is meant to evaluate environmental technologies that address compliance and pollution prevention.

9. Schedule of Activities

The Gantt chart (figure 21) represents the project milestones for laboratory validation and demonstration on HHA.

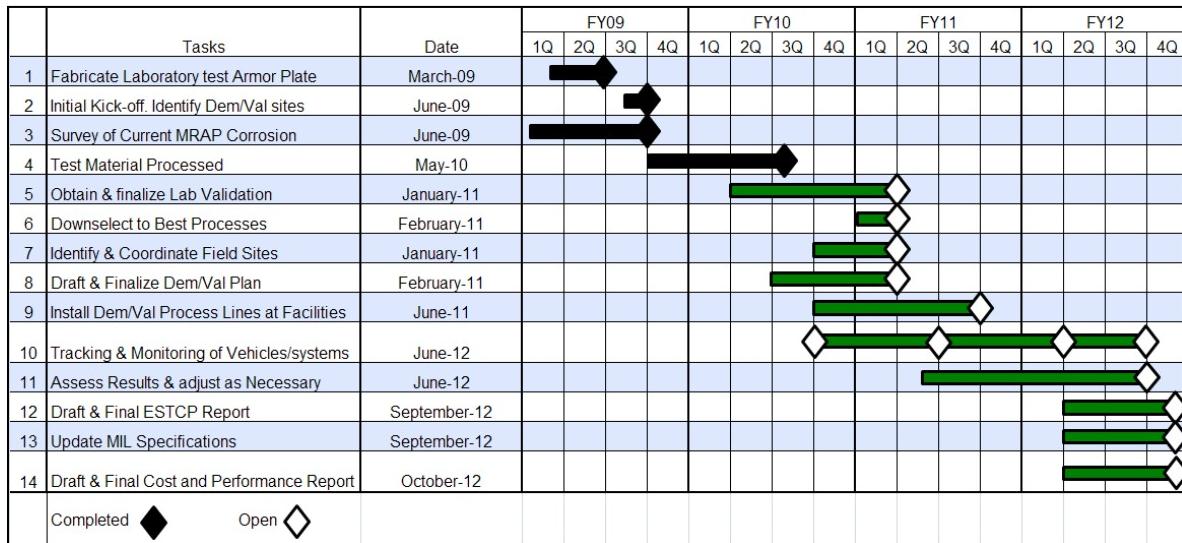


Figure 21. Gantt chart for execution of the demonstration project.

10. Management and Staffing

Figure 22 is a flow chart of the demonstration team leads and individual responsibilities:

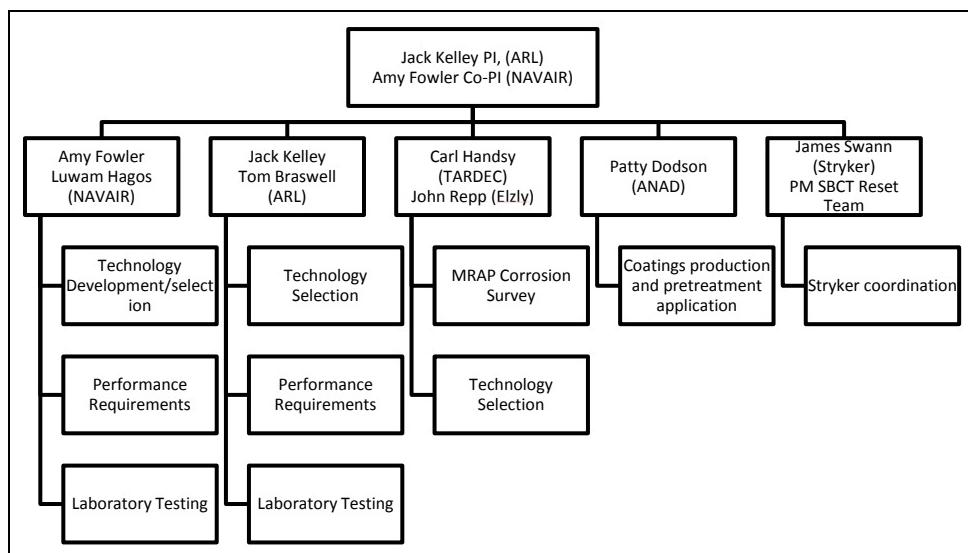


Figure 22. Diagram illustrating demonstration management hierarchy.

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Appendix A. Joint Test Protocol

This appendix appears in its original form, without editorial change.

Joint Test Protocol

Validation of Pretreatments for Steel Armor

Draft

March 17, 2011

Distribution Statement "A" applies.
Approved for public release; distribution is unlimited.

*Prepared and Submitted by the
U.S. Army Research Laboratory,
Corrosion Science and Engineering Team,
Aberdeen, Md.*

*Format and context of this report were developed using
Joint Test Protocol
J-01-GV-002-P2
Validation of Corrosion Protection for
Ground Vehicle Frame Structures
Draft
July 20, 2007*

JTP Approved & Authorized By:

Name, Organization, Date

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APPENDIX

APPENDIX: List of Stakeholders and List of Contributors A-1

ACRONYM LIST

A2LA	American Association for Laboratory Accreditation
ACDT	Accelerated Corrosion Durability Test
AISI	American Iron and Steel Institute
ANSI	American National Standards Institute
ARDEC	U.S. Army Armament Research, Development and Engineering Center
ARL	U.S. Army Research Laboratory
ASTM	American Society for Testing and Materials
ATC	U.S. Army Aberdeen Test Center
BP	Best Performance
CARC	Chemical Agent Resistant Coating
cfm	Cubic Feet per Minute
COTS	Commercial Off-the-Shelf
CPC	Corrosion Preventive Compound
CTC	Concurrent Technologies Corporation
DoD	Department of Defense
HSLA	High-Strength Low-Alloy
IP	Improved Performance
JG-PP	Joint Group on Pollution Prevention
JTP	Joint Test Protocol
JTR	Joint Test Report
kPa	Kilopascal
lb	Pound
mg	Milligram
mm	Millimeter
MMC	Metal-Matrix Composite
MP	Minimum Performance
NLT	Not Less Than
NSS	Neutral Salt Spray
NVLAP	National Voluntary Laboratory Accreditation Program
PFL	Product Failure Laboratory
psi	Pounds per Square Inch
QPL	Qualified Products List
SAE	Society of Automotive Engineers
SS	Salt Spray
TACOM	U.S. Army Tank-automotive and Armaments Command
TDPMD	Technology Demonstration for Prevention of Material Degradation
U.S.	United States
VOC	Volatile Organic Compound
VPSA	Validation of Pretreatments for Armor Steel

PREFACE

This Joint Test Protocol (JTP) was prepared by the Army Research Laboratory Corrosion Science and Engineering Team. The objective of this JTP is to select and implement the most appropriate approaches for the improvement of the control of material degradation on Army materiel and assets, thereby reducing life cycle operational costs and maximizing equipment sustainability for the warfighter.

Format and context of this report were developed using Joint Test Protocol J-01-GV-002-P2 Validation of Corrosion Protection for Ground Vehicle Frame Structures (Draft), July 20, 2007. The depth of technical content of this JTP was determined by technical associates, pertinent United States (U.S.) Army personnel, government contractors, and other government and commercial technical representatives (hereafter referred to as “stakeholders”) who are participants in the Integrated Product Team (IPT) of the ESTCP funded project for Non-Chromate Zero-VOC Coatings for Army and Navy Ground Vehicles.

JTP REVISIONS HISTORY

This section will serve as a means to document revisions and discussions regarding this JTP only. It is intended to help the reader identify updated versions of the JTP, and to organize periodic updates of the JTP as new materials and techniques become available. If the latest entry on the JTP Revisions History is more than two (2) years old, the entry "No revisions have been made for the year 20xy" will be entered where appropriate.

1.0 INTRODUCTION

This JTP contains the critical requirements and tests necessary to evaluate pretreatment technologies for use on U.S. military steel armor. The JTP provides a standard set of tests and test conditions that the manufacturers, the U.S. military, and third-party testing organizations may use to fairly gauge how the technology compares to existing technologies. With the test results presented in a Joint Test Report (JTR), the manufacturer and military can make an informed decision with regard to subjecting the technology to qualification testing for inclusion on the Qualified Products List (QPL). This document is a protocol for testing and assessing the performance of any potential corrosion prevention pretreatment, or any repair process or maintenance process involving steel armor. The potential technologies for consideration will hereafter be referred to simply as “candidates.” Candidate steel pretreatment processes shall not exceed 160°C in order to qualify for testing.

1.1 Scope

This JTP establishes the corrosion-resistance performance requirements that must be met for a candidate to be considered for use on military steel armor. Military steel armor is considered that which meets the specifications described in MIL-A-46100. Other properties of potential candidates will also be considered (see Feasibility Study discussion in the next section). However, evaluations of these properties are specific to the application, and will be considered acceptable based only upon equal or improved performance when compared to the corrosion protection system currently being used.

It must be emphasized that this JTP document is not a process, material, or product specification, nor is it intended to address ongoing quality issues. The testing outlined in this document confirms the technical capabilities of the candidate for the particular application with respect to corrosion resistance, and qualifies the candidate for consideration for military use by the relevant armed services’ Corrosion Office invoking the JTP (e.g., the Army Corrosion Manager) or the relevant Program Manager (hereafter referred to as the “invoking authority”). ***It should also be emphasized that successful completion of the procedures outlined in this JTP does not obligate the U.S. Army or any other DoD organization to procure or use the candidate.***

1.2 Execution

This document is organized in such a manner to aid the user during the corrosion study planning stage, through the testing activity, and during the data reporting and interpretation phases. This section describes the use of this document by outlining the steps that will guide the user through the process of extracting and utilizing the corrosion data. Section 2.0 describes a logical flow to the process of evaluating the results of the corrosion tests and comparing the properties of the candidate with the established criteria necessary to qualify the candidate for potential military use. Section 2.0 also provides a test flow diagram and examples of situations in which the JTP could be used. Section 3.0 discusses application scenarios, the test method matrix, and methodology. Section 4.0

describes test requirements (acceptance criteria) and procedures. Section 5.0 discusses failure analysis. Finally, Section 6.0 provides a list of reference documents that were utilized in the preparation of this JTP.

The corrosion-resistance performance of candidates evaluated using this JTP will be determined through a series of tests. These tests have been derived from engineering, performance, and operational impact (supportability) standards defined by a consensus of government and industry participants. The tests in this document are based upon recognized commercial and military test standards that are currently in use by established test facilities. In instances where the JTP test method conflicts with the reference standard on which it is based, the JTP test method will take precedence. This JTP also provides guidelines for the screening of candidates (Screening Tests), in cases where initial viability must be assessed before conducting the Performance and Special Tests or for urgent short-run applications.

Prior to conducting the required tests, a candidate must undergo a preliminary Feasibility Study, in which the following considerations shall be addressed:

- The candidate must be evaluated using those tests that define the performance levels of Chemical Agent Resistant Coatings (CARCs) , per MIL-DTL-53072, Chemical Agent Resistant Coating (CARC) System Application Procedures And Quality Control Inspection. The candidate must demonstrate compatibility with the existing CARC system, with no adverse effects on the CARC properties. Relevant test methods and military standards are defined in MIL-C-53072D. . Since CARC compatibility testing involves the use of chemical agents, the U.S. Army Research Laboratory (ARL) will conduct these tests on test specimens supplied by the vendor, at the vendor's expense.
- The candidate must conform to current military environmental regulations and concerns, such as atmospheric and groundwater impact, volatile organic compound (VOC) content, waste disposal, etc.
- Procurement of the candidate must be compatible with standard military business procedures. Considerations include, but are not limited to: distribution status (domestic/offshore), product cost analysis, and vendor capability, reputation, and reliability.

The Feasibility Study shall be conducted prior to the execution of the test program contained in this JTP. The business issues assessment shall be conducted again at the completion of the JTP testing if business issues have changed as a result of product and/or financial changes. The actual implementation of the Feasibility Study shall be conducted under the authority of the invoking authority, and is outside the scope of this JTP.

The tests outlined in this JTP are organized into three general areas, Screening, Performance, and Special Testing. Screening Testing involves those tests the vendor may decide to perform if limited data exists to determine the candidate's ability to pass the Performance Tests, or tests that the invoking authority may require for urgent short-run

applications. Performance Testing involves those tests required for evaluating any pretreatment candidate for use on steel armor. Special Testing includes those tests identified by some (but not all) stakeholders for evaluating any pretreatment candidate for use on steel armor in special applications, such as exposure to particularly unusual environments. The candidate must meet both Performance and applicable Special Testing requirements to be considered for special applications.

A JTR will document the testing conducted on each candidate in accordance with this JTP. The JTR will provide a record of test specifics, such as candidate test specimen and substrate preparation, application process, test equipment model and calibration, laboratory environmental conditions, and test results. If planned execution of the tests varies from that described in this JTP, test procedure modifications must be approved by the stakeholders and the invoking authority in advance and documented in the JTR. The JTR will be used as a reference for future corrosion-prevention endeavors by other DoD and commercial users to minimize duplication of effort.

1.3 Document Maintenance

Annual updates and general maintenance of this document will be the responsibility of a committee chaired by the Army Corrosion Office or designee. The document will be reviewed and updated on an annual basis with changes being noted on the “JTP Revisions History” page. If no changes have been made, the entry “no revision has been made for the year 20xy” will be entered where appropriate. This document is considered to be obsolete if the latest entry on the JTP Revisions History is more than two years old. In this case, contact the Army Corrosion Office or designee for the most recent revisions before conducting testing in accordance with this JTP.

2.0 JTP DOCUMENT GUIDE

This section of the JTP facilitates the use of this document by providing a logical implementation flow process as well as examples of JTP evaluations for several candidates. Use of this document for military consideration of a candidate utilizing the Performance and Special Testing sections, and the preliminary screening of untried candidates using the Screening Tests, is described and demonstrated.

Figure 1 illustrates the process flow for conducting Screening, Performance, and Special Tests, as well as the retesting of candidates that have failed one of the aforementioned tests. The evaluation process begins with the Feasibility Study. If the candidate conforms to current military environmental regulations, and procurement of the candidate is compatible with standard military business procedures, the testing required is determined via the Test Method Matrix (presented later in Table 1).

The Screening Tests have been established so that preliminary screening of newer, unproven candidates can be conducted. The decision of whether or not to utilize Screening Tests before conducting Performance and Special Tests lies solely with the invoking authority. Successful completion of the Screening Tests qualifies a candidate for continued testing under the Performance Tests or evaluates the performance for qualitative purposes only. Screening Tests can also be used in instances where a small production run is required, and/or where expedited use is required for a limited application. However, consideration of a candidate for generalized military use, as defined in this JTP, can be accomplished only by successful completion of the Performance Tests, and Special Tests for special applications.

Any candidate that is to be considered technically acceptable must meet at least the Minimum Performance (MP) criteria for each Performance or Special Test, as established in Section 4.0, Testing Requirements, Descriptions and Procedures.

A failure analysis can be performed on any test specimen that fails Screening, Performance, or Special Tests to determine the cause of failure (see Section 5.0). Failure in any test does not necessarily disqualify a candidate for use in all possible applications; however, use of a candidate that has failed Screening, Performance, or Special Tests is at the discretion of the invoking authority, and is outside the scope of this document. Following completion of testing and/or failure analysis, the JTR is forwarded to the vendor for transmittal to the invoking authority for review.

Note that, in Figure 1, there are potential “infinite loops” that might occur due to continual testing failures. To resolve this, the following procedure is to be followed. If failure is still occurring after the third cycle for any of the Screening Tests, the testing process is to end, the failures are to be documented in the JTR, and the JTR is to be forwarded to the vendor for transmittal to the invoking authority for review and response. This procedure is likewise applicable for the Performance and Special Tests.

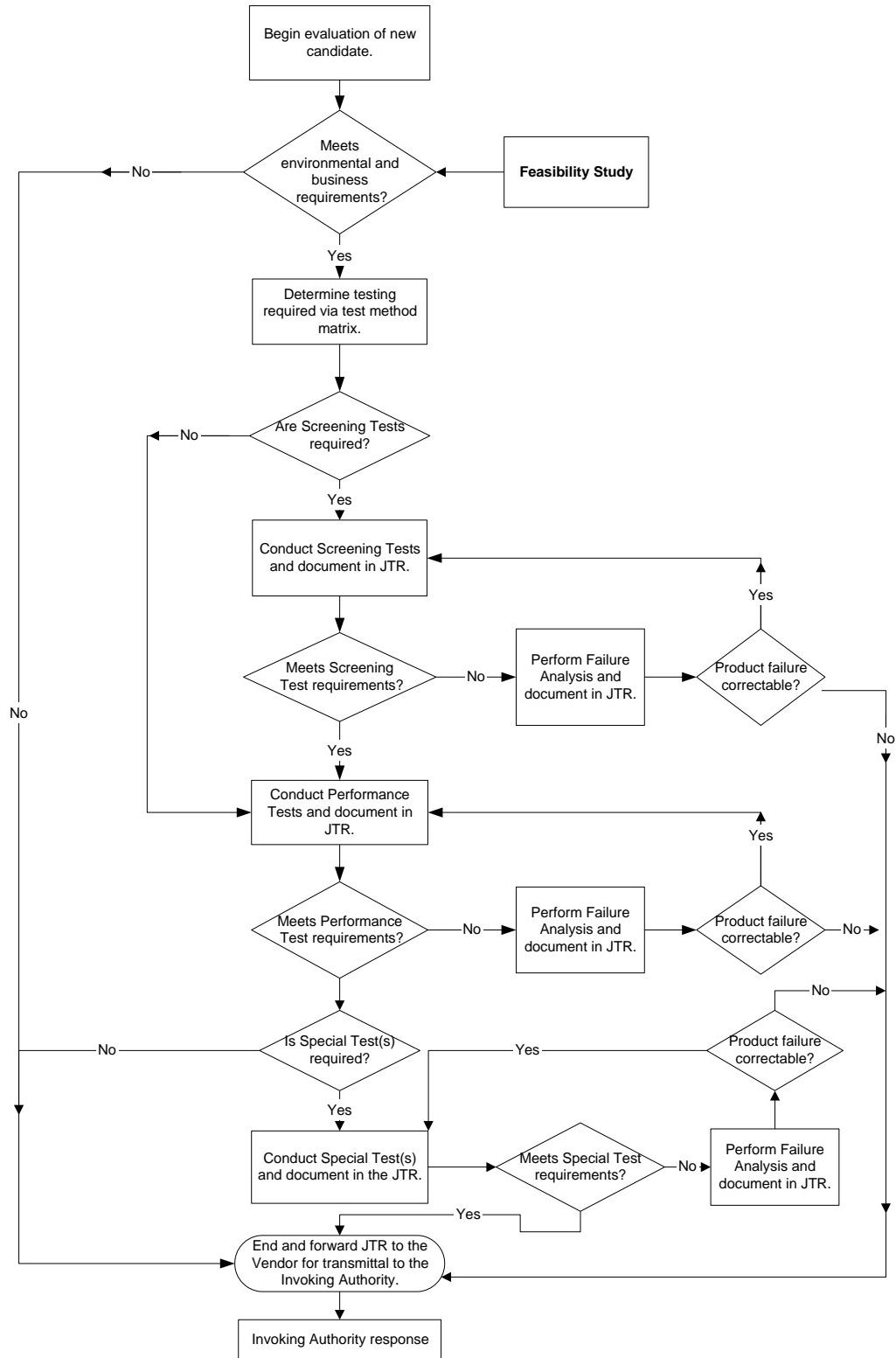


Figure 1. Test Flow Diagram

The following three examples are provided to demonstrate how this JTP can be used for Screening, Performance, and Special Testing situations.

Example # 1

SITUATION: A vendor has developed a new conversion coating system to be considered for use on only steel armor for a special urgent short-run application.

EVALUATION:

1. The VPSA JTP directs the users to the JTP Test Flow Diagram (Figure 1). The Feasibility Study is conducted, and initial assessments regarding CARC compatibility, environmental concerns, and overall business risk are determined.
2. The invoking authority determines that Screening Tests only will be necessary for this system, and that, if the outcome is positive, qualification will be via a waiver (which is beyond the scope of this document). The JTP Test Flow Diagram leads the users to the Test Method Matrix (Table 1) to determine the testing required for screening.
3. The relevant test lab personnel begin the screening evaluation of the conversion coating.
4. A JTR is written documenting the results of the Screening Tests.
5. Screening Test results demonstrate acceptable performance relative to the other approved coating systems.
6. The JTR is submitted to the vendor for transmittal to the invoking authority for review. The invoking authority, if satisfied, issues a waiver/deviation (which is outside the scope of this JTP) to authorize the new conversion coating for this limited special short-run application.

RESULT: The JTP provides guidelines regarding testing and performance levels for preliminary risk reduction for this urgent short-run requirement.

Example # 2

SITUATION: A vendor proposes a new pretreatment / conversion coating, an inhibitor spray, to be considered for use on steel armor.

EVALUATION:

1. The VPSA JTP directs the users to the JTP Test Flow Diagram. The Feasibility Study is conducted, and initial assessments are made regarding CARC compatibility, environmental concerns, and overall business risk.
2. The vendor decides that, since the candidate is new, the candidate will be subjected to Screening Tests prior to the initiation of the Performance Tests. The JTP Test Flow Diagram leads the users to the Test Methods Matrix to determine the testing required for effective screening.

3. The relevant test lab personnel begin the screening evaluation of the pretreatment spray.
4. A JTR is written documenting the results of the Screening Tests and is forwarded to the vendor.
5. Screening Test results indicate that the pretreatment shows promise, as the corrosion performance level improved significantly as compared to the current corrosion protection system.
6. The relevant test lab personnel conduct Performance Tests per the Test Method Matrix.
7. A JTR is written documenting the results of the Performance Tests and is forwarded to the vendor for transmittal to the invoking authority for review.

RESULT: The JTP establishes the requirements for consideration, as well as guidelines for preliminary testing (Screening Tests), and provides the methodology for documenting the relative performance of the candidate compared to current corrosion protection systems.

3.0 APPLICATION SCENARIOS

3.1 Guidelines

This section establishes the guidelines for testing a potential candidate for corrosion protection of steel armor, given various application scenarios.

A generic model of a candidate and the various layers of materials that may be applied to the substrate to establish a corrosion protection system are shown in Figure 2.

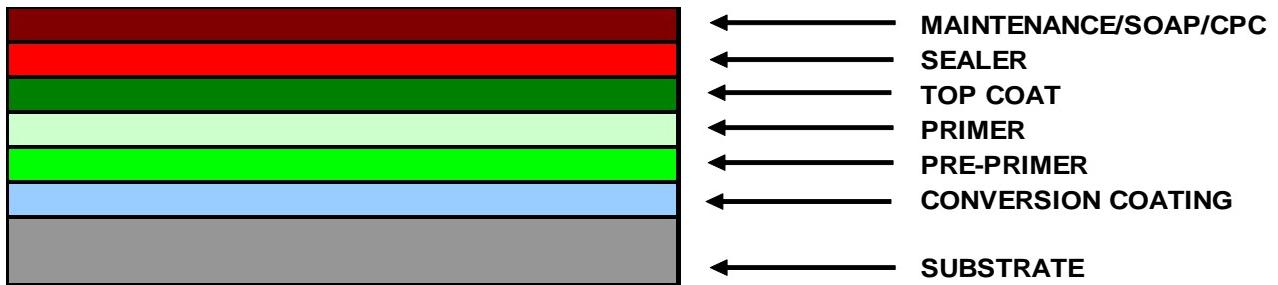


Figure 2. Generic Substrate and Corrosion Protection System Model (not to scale)

The above model represents a generic coating system with numerous layers of constituent materials that may be included as part of a candidate corrosion protection system. Using this approach, guidelines for Screening, Performance, and Special Test procedures can be derived, even if the candidate consists of only some of the constituent layers shown in Figure 2.

Table 1 lists the tests to be applied for Screening, Performance, and Special Tests, as well as the location of the test procedure within the JTP document.

Table 1. Test Method Matrix

SCREENING TESTS (conducted on coupons, about 1 month in duration)	JTP Section
Adhesion (Pull-off)	4.4.3
Corrosion Resistance (Neutral Salt Spray (Fog))	4.4.5
PERFORMANCE TESTS (conducted on actual or simulated parts, about 6 months in duration)	JTP Section
Adhesion (Dry)	4.4.1
Adhesion (Wet)	4.4.2
Adhesion (Pull-off)	4.4.3
Corrosion Resistance (Cyclic)	4.4.4
Corrosion Resistance (Neutral Salt Spray (Fog))	4.4.5
Chip Resistance	4.4.6
Stress-Corrosion Cracking	4.4.7
SPECIAL TESTS (conducted on actual or simulated parts, up to 5 years in duration)	JTP Section
Field Exposure, Static	4.4.8
Field Exposure, On-Vehicle	4.4.9

The guidelines for testing candidates under this JTP are as follows:

1. Select the test specimens or proposed steel armor, or manufactured parts that accurately simulate current production material, for testing of the candidate.
2. Obtain approval for test procedure modification if applicable.
3. Perform appropriate testing and obtain test results.
4. Submit JTR to the vendor for transmittal to the invoking authority for review.

3.2 Methodology

Screening Tests shall be conducted on test panels made from the same material or alloy as the actual steel armor. The actual processes to be used in the preparation of the test panels shall be outlined in the JTR.

Performance and Special Tests shall be conducted on sections of actual steel armor, or manufactured parts that accurately simulate current production material and manufacturing processes. Mechanical conditions such as bends, welds, fasteners,

crevices, etc., shall be incorporated when applicable. The actual processes used in the test specimen preparation shall be outlined in the JTR.

4.0 TESTING REQUIREMENTS, DESCRIPTIONS AND PROCEDURES

The stakeholders have established the requirements necessary to evaluate corrosion-resistant candidates for use on U.S. military steel armor. These requirements have been used to identify test methods, derive test procedures, and establish acceptance criteria.

Screening Test methods are identified along with acceptance criteria in Section 4.1. Performance Test methods are identified along with acceptance criteria in Section 4.2.

Special Test methods are identified along with acceptance criteria in Section 4.3. These are program-specific requirements identified by at least one of the stakeholders. Special Tests are performed on sections of actual armored vehicles or manufactured parts that accurately simulate current production material and manufacturing processes.

It is recommended that different examples of substrates utilizing the candidate, if applicable, be tested concurrently to obtain maximum benefit from the testing effort. Questions regarding the different substrate materials shall be directed to the invoking authority.

The candidate must pass the Performance and applicable Special Tests with at least Minimum Performance (MP) in order to be considered for military use. Acceptance criteria for Improved Performance (IP) and Best Performance (BP) are provided as well, so that improved corrosion resistance with respect to the current corrosion protection system can be quantified.

In instances where the JTP test method conflicts with the reference standard on which it is based, the JTP test method shall take precedence.

All testing shall be performed at the vendor's expense by a government or independent testing laboratory, which shall be agreed upon by the stakeholders. The independent testing laboratory must either be accredited by a recognized governing body (such as the American Association for Laboratory Accreditation (A2LA) or the National Voluntary Laboratory Accreditation Program (NVLAP)), or be an ISO 9001 certified company having its own testing laboratory. **Testimonials shall be used for informational purposes only, and are not to be used in lieu of tests required under this JTP.** Incorporation of previous studies performed on the candidate by an outside laboratory, at the request of the vendor, is at the discretion of the invoking authority.

All tests shall be conducted in a manner that will eliminate duplication and maximize the use of each test specimen. Where possible, more than one test shall be performed on each specimen. The number and types of tests that can be run on any one specimen will be dependant upon the degree of alteration imparted to the sample from previous tests. Failure in any test does not necessarily disqualify a candidate for use in all possible applications; however, acceptance of a candidate that has failed Screening, Performance, or Special Tests is at the discretion of the invoking authority. In this case, use of the

candidate will be justified by a special waiver, which is outside the scope of this document.

The tests described in this JTP may involve the use of hazardous materials, operations, and/or equipment. This JTP does not address all safety issues associated with their use. It is the responsibility of each user of this JTP to establish appropriate safety and health practices, and to determine the applicability of regulatory limitations, prior to the use of such materials, operations, and/or equipment.

The following conditions will apply to all Screening, Performance, and Special Testing, unless otherwise specified in an individual test description:

- It is preferred that all test panels be produced from the same material lot.
- It is suggested that at least three specimens be used for Screening Tests, and at least five specimens be used for Performance and Special Tests.
- Unless otherwise specified, all test specimens shall be cleaned prior to pretreatment to ensure surfaces are free of water breaks in accordance with the latest version of American Society for Testing and Materials (ASTM) G1, “Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens.”
- Pretreatment of the test specimens will be dependant upon the candidate under scrutiny, and shall be specified in the JTR.

It is recommended that users of this JTP obtain copies of previous JTRs, if available, from the invoking authority for additional test details or minor modifications that were necessary in the execution of previous testing.

4.1 Screening Testing Requirements

Table 2 lists all Screening Testing requirements identified by stakeholders for evaluating candidates on steel armor.

Table 2. Screening Testing Requirements

JTP Section	Test	Acceptance Criteria	Test Method References
4.4.3	Adhesion (Pull-off)	Meets or exceeds adhesion strength of DoD-P-15328 on similarly prepared abrasive blasted surface of 1.5 mil profile or 1200 psi	ASTM-4541 Pull-off Adhesion
4.4.5	Corrosion Resistance (Neutral Salt Spray (Fog))	After 336 hrs of exposure: Steel substrate rating ≥ 7 scribed	ASTM B117 ASTM D714 ASTM D1654

Screening Tests are performed on test panels made from steel armor-representative substrate material. It is preferred that all test panels be produced from the same material lot, and it is desirable that the processing pedigree be well documented in the JTR. The candidate must pass the acceptance criteria of each Screening Test. Results of the Screening Tests are reported in the JTR and submitted to the vendor for transmittal to the invoking authority.

The Screening Tests (identified in Table 2) are further defined in Section 4.4, with test descriptions, scope, and methodology. Also included are any major or unique equipment and instrumentation requirements, reagents, procedures, and acceptance criteria. The procedure identifies the test specimen preparation, test procedure, and method for collecting and reporting test results.

4.2 Performance Testing Requirements

Table 3 lists all Performance Testing requirements identified by stakeholders for evaluating candidates on commonly used steel armor substrates. The tests (listed below) shall be conducted for non-traditional candidate substrates such as high-hardness (greater than Rockwell hardness Rc35), (HHA) steels and high-strength low-alloy (HSLA) steels.

A material/corrosion design review will be conducted by the invoking authority to determine if hydrogen embrittlement, corrosion fatigue, or stress-corrosion cracking could occur based on the material and potential exposure environment. However, shall be known that HHA has hardnesses well over Rc35 and is susceptible to environmentally assisted cracking (EAC) whenever residual stresses are present. The invoking authority will specify the appropriate mechanical stability testing required, and the vendor will contract with an independent, certified lab to perform the required tests.

The criteria for determining a risk candidate for hydrogen embrittlement are as follows:

1. Any ferrous-based alloy exhibiting hardness greater than Rc35 (e.g., high-strength steel) requires testing and heat treatment according to Federal Specification TT-C-490, "Cleaning Methods for Ferrous Surfaces and Pretreatments for Organic

Coatings.” . Testing is recommended for materials that will be exposed to an electrochemical environment where hydrogen evolution can occur (e.g., electroplating, pickling).

The basic criteria for determining a risk candidate for stress-corrosion cracking are as follows:

1. Any material that will be exposed to a corrosive environment known to cause stress-corrosion cracking, such as sodium hydroxide for carbon steel or chloride ions for stainless steels, and tensile stress due to applied load or residual stresses such as those produced by welding (e.g., any material that will experience a stress greater than 50% of the yield stress) shall be tested.
2. Any material that is known to be subject to stress-corrosion cracking (determine susceptibility by conducting a literature search or consulting with a corrosion expert) shall be tested.

Table 3. Performance Testing Requirements

JTP Section	Test	Acceptance Criteria, Minimum Performance (MP)	Acceptance Criteria, Improved Performance (IP)	Acceptance Criteria, Best Performance (BP)	Test Method References
4.4.1	Adhesion (Dry)	Adhesion rating (steel) \geq 4B; adhesion rating	N/A	Adhesion rating (steel) = 5B; adhesion rating	ASTM D3359
4.4.2	Adhesion (Wet)	Scribed area rating (steel) \geq 3A after 24 hours at ambient;	Scribed area rating (steel) \geq 3A after 96 hours at 120°F; 168 hours at 150°F;	Scribed area rating (steel) \geq 4A after 168 hours at 150°F;	ASTM D3359
4.4.3	Adhesion (Pull-off)	Minimum average 30 events rating of 1200 PSI	Minimum average 30 events rating of 1800 PSI	Minimum average 30 events rating of 2500 PSI	ASTM D 4541
4.4.4	Corrosion Resistance (Cyclic)	After 60 cycles: steel substrate rating \geq 4 scribed	After 60 cycles: steel substrate rating \geq 6 scribed	After 60 cycles: steel substrate rating \geq 8 scribed	GM 9540 ASTM D714 ASTM D1654
4.4.5	Corrosion Resistance (Neutral Salt Spray (Fog))	After 500 hours of exposure: steel substrate rating \geq 6 scribed	After 750 hours of exposure: steel substrate rating \geq 6 scribed	After 1000 hours of exposure: steel substrate rating \geq 6 scribed	ASTM B117 ASTM D714 ASTM D1654

NLT = Not Less Than

Table 3. Performance Testing Requirements (Continued)

JTP Section	Test	Acceptance Criteria, Minimum Performance (MP)	Acceptance Criteria, Improved Performance (IP)	Acceptance Criteria, Best Performance (BP)	Test Method References
4.4.6	Chip Resistance	After one cycle, chip rating NLT 5B for steel,	After one cycle, chip rating NLT 7C for steel,	After one cycle, chip rating NLT 9C for steel,	SAE J400
4.4.7	RSL Stress-Corrosion Cracking	There shall be no detrimental effect to K1c of substrate. High Hard K1c @ 48-51Rc shall maintain $K_{1eac} \geq 19$ (ksi/in)			ASTM E 399-97 ASTM G30 ASTM G38 ASTM G39 ASTM G47

NLT = not less than

Performance Tests are performed on sections of actual steel armor or manufactured parts that accurately simulate current production material and manufacturing processes. Results of the Performance Tests are reported in the JTR and submitted to the vendor for transmittal to the invoking authority.

The Performance Tests (identified in Table 3) are further defined in Section 4.4, with test descriptions, scope, and methodology. Also included are any major or unique equipment and instrumentation requirements, reagents, procedures, and acceptance criteria. The procedure identifies the test specimen preparation, test procedure, and method for collecting and reporting test results.

4.3 Special Testing Requirements

Table 4 lists Special Testing requirements identified and required by some (but not all) stakeholders for evaluating candidates.

Table 4. Special Testing Requirements

JTP Section	Test	Acceptance Criteria, Minimum Performance (MP)	Acceptance Criteria, Improved Performance (IP)	Acceptance Criteria, Best Performance (BP)	Test Method References	Branch/ Stakeholders/ Service Requiring Test
4.4.8	Field Exposure, Static	Three years of exposure: specimen has a minimum of 25% less creepage from scribe than current corrosion protection system	Four years of exposure: specimen has a minimum of 50% less creepage from scribe than current corrosion protection system	Five years of exposure: specimen has a minimum of 75% less creepage from scribe than current corrosion protection system	Approved test site standard practice ASTM G50 ASTM G7 ASTM D1654	As required by the invoking authority
4.4.9	Field Exposure, On-Vehicle	Three years of exposure: steel substrate rating $\geq 5M$ unscrubbed;	Four years of exposure: steel substrate rating $\geq 5M$ unscrubbed;	Five years of exposure: steel substrate rating $\geq 5M$ unscrubbed;	ASTM D1654 ASTM D714	As required by the invoking authority

NLT = not less than

Unless otherwise noted, Special Testing shall be performed on sections of actual steel armor or manufactured parts that accurately simulate current production material and manufacturing processes. Results of the Special Tests are reported in the JTR and submitted to the vendor for transmittal to the invoking authority.

The Special Tests (identified in Table 4) are further defined in Section 4.4, with test descriptions, scope, and methodology. Also included are any major or unique equipment and instrumentation requirements, reagents, procedures, and acceptance criteria. The procedure identifies the test specimen preparation, test procedure, and method for collecting and reporting test results.

4.4 Test Descriptions

4.4.1 Adhesion (Dry) (ASTM D3359)

4.4.1.1 Scope

This test method assesses the adhesion of coatings to substrates by applying and removing pressure-sensitive tape over cuts made in the coating.

4.4.1.2 Equipment

Cutting Tool. A very sharp razor blade, scalpel, knife, or other cutting device having a cutting edge (tip) angle between 15 and 30 degrees.

Cutting Guide. Steel or other hard metal straightedge to ensure straight cuts.

Rule. A steel rule graduated in 0.5-millimeter (mm) (0.02") increments for measuring individual cuts.

Tape. Permacel 99 (1" wide semitransparent pressure-sensitive tape, manufactured by Permacel, New Brunswick, NJ 08903). *NOTE*: Permacel 99 tape has a one-year shelf life. Utilizing the tape after this time may yield inaccurate results.

Roller. A 4.5-pound (lb) rubber-covered roller.

Illumination. A light source to determine whether the cuts have been made through the coating into the substrate.

Dry Film Thickness Gage. A device to measure the thickness of the applied coating.

4.4.1.3 Reagents

None.

4.4.1.4 Procedure

Test Specimens. Prepare at least three test specimens for Screening Testing and at least five specimens for Performance Testing. For Screening Testing, use 102 x 152 mm (4" x 6" test panels, composed of the material that is utilized in the end application. For Performance Testing, sections of actual or simulated armor steel parts shall be used (see Section 3.2).

Preparation. Using test specimens incorporating the candidate, measure the dry film thickness in at least five areas. Make cuts in the coating system per the latest version of ASTM D3359, "Standard Test Methods for Measuring Adhesion by Tape Test – Cross-Cut Tape Test." Remove two laps of tape and discard. Remove an additional length of tape and cut a piece approximately 76 mm (3") long. Place the center of the tape over the grid and smooth into place by passing the roller over the area once.

Test Procedure. Within 90 ± 30 seconds of tape application, remove the tape by holding the free end and rapidly pulling (not jerking) back upon itself at as close to an angle of 180 degrees as possible.

Test Results. Inspect the grid area for removal of coating from the substrate or from a previous coating. Rate the adhesion in accordance with the latest version of ASTM D3359, Test Method B. If ratings differ by more than one rating unit, the results are considered suspect and three additional test specimens for Screening Testing and five additional test specimens for Performance Testing shall be prepared and the tests repeated. If applicable, use these latter ratings in the report.

Report. Report all information per the latest version of ASTM D3359 Test Method B. In addition, report the average of the five dry film thickness measurements (as measured by thickness gauge).

4.4.1.5 Acceptance Criteria

Substrate	Acceptance Criteria, Minimum Performance (MP)	Acceptance Criteria, Improved Performance (IP)	Acceptance Criteria, Best Performance (BP)
Steel	Adhesion rating \geq 4B	N/A	Adhesion rating = 5B

4.4.2 Adhesion (Wet) (ASTM D3359)

4.4.2.1 Scope

This test method describes the procedure and conditions for assessing the wet adhesion of coatings to metallic substrates by applying and removing pressure-sensitive tape over cuts made in the coating.

4.4.2.2 Equipment

Tank and Tank Cover. A tank made from corrosion-resistant materials and large enough to hold the required number of test specimens. The tank cover is required to help maintain water temperature and prevent evaporation.

Heaters. Heaters capable of maintaining the required water temperature (see Section 4.4.2.4, Procedure).

Circulation System. A pump or stirrer required for circulating the water in the water tank, capable of low to moderate agitation speeds.

Test Specimen Supports. Supports constructed of nonconductive and corrosion-resistant materials to hold the coated test specimens 30 mm (1.2") apart and at least 30 mm (1.2") from the bottom and sidewalls of the tank.

Cutting Tool. A very sharp razor blade, scalpel, knife, or other cutting device having a cutting edge (tip) angle between 15 and 30 degrees.

Cutting Guide. Steel or other hard metal straightedge to ensure straight cuts.

Rule. A steel rule graduated in 0.5-mm (0.02") increments for measuring individual cuts.

Tape. Permacel 99 (1" wide semitransparent pressure-sensitive tape, manufactured by Permacel, New Brunswick, NJ 08903). *NOTE*: Permacel 99 tape has a one-year shelf life. Utilizing the tape after this time may yield inaccurate results.

Roller. A 4.5-lb rubber-covered roller.

Illumination. A light source to determine whether the cuts have been made through the coating to the substrate.

Dry Film Thickness Gage. A device to measure the thickness of the applied coating.

4.4.2.3 Reagents

Distilled Water. Conforming to Type IV water as described in the latest version of ASTM D1193.

4.4.2.4 Procedure

Test Specimens. At least three test specimens shall be used for Screening Testing and at least five specimens for Performance Testing. For Screening Testing, use 102 x 152 mm (4" x 6") test panels, composed of the material that is utilized in the end application. For Performance Testing, use sections of actual or simulated steel armor (see Section 3.2).

Preparation. Using test specimens incorporating the candidate, measure the dry film thickness in at least five areas.

Test Procedure. For the Screening and Minimum Performance Tests, immerse the test specimens in ambient (room temperature) distilled water for 24 hours. For Improved Performance, immerse the test specimens in distilled water maintained at $49 \pm 2^\circ\text{C}$ ($120 \pm 4^\circ\text{F}$) for 96 hours. For Best Performance, immerse the test specimens in distilled water maintained at $66 \pm 2^\circ\text{C}$ ($150 \pm 4^\circ\text{F}$) for 168 hours. Remove the test specimens from the water and wipe dry with a soft cloth. Within 90 ± 30 seconds after removal from the water, make cuts in the coating system with two parallel lines, 19 mm (0.75") apart, and place an "X" scribe within the parallel lines. Make the "X" lines about 38 mm (1.5") long and intersecting at 30–45 degrees in the center of the parallel lines. Remove two laps of tape and discard. Remove an additional length of tape and cut a piece approximately 75 mm (3") long. Place the center of the 25 mm (1") wide tape over the center of the "X" and smooth into place by passing the roller over the area once. Remove the tape by holding the free end and rapidly pulling (not jerking) back upon itself at as close to an angle of 180 degrees as possible.

Test Results. Rate the adhesion in accordance with the latest version of ASTM D3359, Method A "Measuring Adhesion by Tape Test – X-Cut Tape Test."

Report. Report all information per the latest version of ASTM D3359, Method A. In addition, report the average of the five dry film thickness measurements.

4.4.2.5 Acceptance Criteria

Parameter	Acceptance Criteria, Minimum Performance (MP)	Acceptance Criteria, Improved Performance (IP)	Acceptance Criteria, Best Performance (BP)
Scribed Area Rating	$\geq 3A$	$\geq 3A$	$\geq 4A$
Immersion Period	24 hours	96 hours	168 hours
Water Temperature	ambient	49°C (120°F)	66°C (150°F)

4.4.3 Adhesion (Pull off) (ASTM D-4541)

4.4.3.1 Scope

This test method covers a procedure for evaluating the pull-off strength (commonly referred to as adhesion) of a coating by determining either the greatest perpendicular force (in tension) that a surface area can bear before a plug of material is detached, or whether the surface remains intact at a prescribed force (pass/fail). Failure will occur along the weakest plane within the system comprised of the test fixture, adhesive, coating system, and substrate, and will be exposed by the fracture surface. This test method maximizes tensile stress as compared to shear stress applied by other methods, such as

scratch or knife adhesion, and results may not be comparable. Further, pull-off strength measurements depend upon both material and instrumental parameters. Results obtained using different devices or results for the same coatings on substrates having different stiffness may not be comparable.

4.4.3.2 Equipment

Adhesion Tester. Commercially available or comparable apparatus as described in Annex A1-Annex A4 of ASTM D 4541.

Loading Fixtures. Devise having a flat surface on one end that can be adhered to the coating and a means of attachment to the tester on the other end.

Detaching Assembly. (adhesion tester) A central grip for engaging the fixture.

Base. Part of the detaching assembly, or an annular bearing ring if needed for uniformly pressing against the coating surface around the fixture either directly , or by way of an intermediate bearing ring. A means of aligning the base is needed so that so that the resultant force is normal to the surface and a means of moving the grip away from the base in as smooth and continuous manner as possible so that a torsion-free, co-axial (opposing pull of the grip and push of the base along the same axis) force results between them.

Timer. Means of limiting the rate of stress to less than 150 psi/s (1PPa/s) so that the maximum stress is obtained in less than about 100s. A timer is the minimum equipment when used by the operator along with the force indicator.

4.4.3.4 Procedure

Test Specimens. At least 10 test pulls shall be used for the Screening Testing and at least 30 test pulls shall be used for the Performance Testing.

Preparation. There are a few physical restrictions imposed by the general methods and apparatus. The following requirements apply:

The selected test area must be a flat surface large enough to support the test fixture.

The selected area must have enough perpendicular and radial clearance and be rigid enough to support the counter force.

Test Procedure. Clean the loading fixture and the coating surface to be bonded. Use care to select only those solvents which will not attack the coating and/or leave residues on the fixture. Prepare the adhesive in accordance with the adhesive manufacturer's recommendations. Apply the adhesive to the fixture or the surface to be bonded using a procedure recommended by the adhesive manufacturer being certain the entire bonding surface is covered. Based on the manufacturer's recommendations, allow enough time for the adhesive to cure. Carefully connect the central grip of the detaching assembly to the loading fixture without bumping, bending, or otherwise prestressing the sample and connect the detaching assembly to its control mechanism, if necessary. After setting the force indicator to zero, increase the load to the fixture in as smooth and continuous manner as possible, at a rate of less than 150 psi/s (1 MPa/s) so that failure occurs or the maximum stress is reached in about 100 s or less.

Test Results. Rate the average results of each set of events.

4.4.3.5 Acceptance Criteria (See Table 3)

Substrate	Screening Test	Acceptance Criteria, Minimum Performance (MP)	Acceptance Criteria, Improved Performance (IP)	Acceptance Criteria, Best Performance (BP)
Steel	Minimum average 10 events rating of 1200 PSI	Minimum average 30 events rating of 1200 PSI	Minimum average 30 events rating of 1800 PSI	Minimum average 30 events rating of 2500 PSI

4.4.4 Corrosion Resistance (Cyclic) (GM 9540P)

4.4.4.1 Scope

This test method describes a field-correlated, laboratory corrosion test method for determining cosmetic corrosion performance that provides a combination of cyclic conditions (salt solution immersion, temperature, and humidity) to accelerate the corrosion process.

4.4.4.2 Equipment

Test Cabinet. Test cabinet with the ability to obtain and maintain the required environmental conditions as specified in GM9540P.

Scribe Tool. An ANSI B 94.50, style E scribe.

Imaging System. A means of visually recording corrosion effects on all test specimens, such as a camera or scanner/software system.

Air Source. A source of clean, dry compressed air capable of delivering at least 10 cfm at 80 psi.

Scale. A ruler with 1-mm (0.04") divisions.

Balance. A digital electronic balance capable of weighing up to 10,000 mg with an accuracy of $\pm 1\%$.

Straightedge. Any straightedge of sufficient length to guide the scribing tool in a straight line.

pH Meter. A meter to measure the pH of the salt solution prior to the start of the test and on a weekly basis thereafter.

Putty Knife. Blunt-edged, 38 mm (1.5") wide.

4.4.4.3 Reagents

Distilled Water. Conforming to Type IV water as described in the latest version of ASTM D1193.

Cleaning Solution. Methanol.

Sodium Chloride. Substantially free of nickel and copper and containing not more than 0.1% sodium iodide and not more than 0.3% total impurities by weight.

Calcium Chloride.

Sodium Bicarbonate.

4.4.4.4 Procedure

Test Specimens. Actual or simulated steel armor shall be used for test specimens (see Section 3.2). The number of test specimens depends on the number of cycles selected for the test exposure duration. Use reference coupons consisting of uncoated 25 x 51 x 3 mm (1" x 2" x 1/8") pieces of any alloy American Iron and Steel Institute (AISI) 1006 through 1010 steel to monitor the average general bare steel corrosion produced by the test environment. The coupon weight in milligrams shall be recorded and retained for future reference. The number of coupons also depends on the number of cycles selected for the test exposure duration. Each test specimen and reference coupon shall be permanently identified by stamping numbers onto the surface.

Preparation. Using test specimens incorporating the candidate, scribe an X scribe through the coating, making sure that the scribed line is all the way through the coating to the substrate. Place the scribed test specimens and reference coupons in the chamber, leaning at an angle of at most 15 degrees from the vertical with the scribed surface facing upwards. Prepare the salt solution per GM9540P and measure the pH prior to the start of the test and on a weekly basis thereafter. Do not attempt to adjust the pH. Clean the reference coupons (bare steel bars) thoroughly with the cleaning solution prior to placing them in the exposure chamber.

Test Procedure. For the MP level, use a test duration of 80 cycles; for the IP and BP levels, use a test duration of 120 cycles. After initially weighing each reference coupon and test specimen, install both the reference coupons and test specimens in the exposure chamber. After every 20 cycles, remove two coupons and two test specimens. Weigh each reference coupon (after removal of the rust layers) and determine the average weight loss for that specific number of cycles. For the test specimens, record the scribe creepback values with respect to average, ASTM-D1654. For the interim creepback measurements, conduct them in a rinsed-only condition. At the final number of cycles, two sets of creepback values will be recorded – one set in a rinsed-only condition and one set after the scrape-and-tape process (see also SAE J2334).

Test Results. At the conclusion of the exposure period (or interim period), remove the test specimens and rinse. Scrape the specimens side-to-side with the putty knife at a 30-degree contact angle. Evaluate the creepage of the test specimens per the latest version of ASTM D1654 for scribed areas and D714 for unscribed. Rate the corrosion or loss of coating extending from the scribe mark (using the worst case for the rinsed or scraped methods) and evaluate the unscribed areas for corrosion spots, blisters, and any other types of failure that may occur. Photographically document each of the test specimens and the reference coupons using the imaging system. Clean the reference coupons using a mild sand (or glass bead) blast to remove all corrosion by-products. Once they are clean, wipe the coupons with methanol and weigh to determine weight loss. Corrosion losses may also be expressed in terms of average corrosion rates from the weight loss,

coupon area, test duration, and metal density by use of the calculation described in ASTM G1.

Report. Report all information required in ASTM D714, and ASTM D1654, including the photographs from the imaging system, and weight loss and/or corrosion rate of the reference coupons.

4.4.4.5 Acceptance Criteria

Parameter	Acceptance Criteria, Minimum Performance (MP)	Acceptance Criteria, Improved Performance (IP)	Acceptance Criteria, Best Performance (BP)
Scribed Area Rating	≥ 4	≥ 6	≥ 8
Unscribed Area Rating	$\geq 5F$	$\geq 7F$	$\geq 9F$

4.4.5 Corrosion Resistance (Neutral Salt Spray (Fog)) (ASTM B117)

4.4.5.1 Scope

This test method describes the procedure and conditions required to create and maintain the neutral salt spray (NSS) (fog) test environment and the evaluation of specimens incorporating the candidate with respect to corrosion, blistering associated with corrosion, loss of adhesion at a scribe mark, or other corrosive attack.

4.4.5.2 Equipment

NSS (Fog) Chamber. This equipment shall consist of a heated fog chamber, a salt solution reservoir, a supply of conditioned (oil- and contaminant-free) compressed air, atomizing nozzles, and specimen supports.

Imaging System. A means of visually recording corrosion effects on all tested specimens, such as a digital camera or scanner/software system.

Scribe Tool. An American National Standards Institute (ANSI) B 94.50, style E scribe.

Straightedge. Any straightedge of sufficient length to guide the scribing tool in a straight line across the specimen surface.

Air Source. A source of clean, dry compressed air capable of delivering at least 10 cubic feet per minute (cfm) at 80 pounds per square inch (psi).

Air Gun and Guard. An air dusting gun and nozzle combination to meet the specification in ASTM D1654. A guard to protect the operator, such as a sandblasting cabinet.

Scale. A ruler with 1-mm (0.04") divisions.

Putty Knife. Blunt-edged, 38 mm (1.5") wide.

4.4.5.3 Reagents

Distilled Water. Conforming to Type IV water as described in the latest version of ASTM D1193.

Sodium Chloride. Substantially free of nickel and copper and containing not more than 0.1% sodium iodide and not more than 0.3% total impurities by weight.

4.4.5.4 Procedure

Test Specimens. At least three specimens shall be used for Screening Testing, and at least five specimens shall be used for Performance Testing. Screening Testing shall be conducted with 102 x 152 mm (4" x 6") test panels, composed of the material that is utilized in the end application. Actual or simulated frame structures shall be used for Performance Testing (see Section 3.2). Each test specimen shall contain a clear identification mark.

Preparation. Using test specimens incorporating the candidate, scribe a single diagonal line through the coating making sure that the scribed line is all the way through to the substrate. Place the scribed test specimens in the chambers, leaning at an angle between 15 and 30 degrees from the vertical with the scribed surface facing upwards. Prepare the salt solution as specified in ASTM B117 such that when atomized at 35°C (95°F), the collected solution is in the pH range of 6.5–7.2.

Test Procedure. Conduct the NSS (fog) test in accordance with the latest version of ASTM B117, "Standard Practice for Operating Salt Spray (Fog) Apparatus." The NSS (fog) chamber shall be operated continuously for the specified number of hours, as shown in Section 4.4.3.5, Acceptance Criteria.

Test Results. At the conclusion of the exposure period, remove the test specimens and clean them by gently flushing with running tap water and drying them with a stream of clean, dry compressed air. Allow the test specimens to recover for 24 hours. Scrape the test specimens side-to-side with the putty knife at 30-degree contact angle. Evaluate the corrosion resistance and creepage of the test specimens in accordance with the latest version of ASTM D1654, "Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments." Rate the corrosion or loss of coating extending back from the scribe mark and evaluate the unscribed areas for corrosion spots, blisters, and any other types of failure that may occur. Use the rating system in ASTM D1654 for scribed areas and D714 for unscribed. Photographically document the surface condition of each of the test specimens using the imaging system.

Report. Report all information required in ASTM B117, D714, and D1654, and include the images from the imaging system.

4.4.5.5 Acceptance Criteria

Parameter	Screening Test	Acceptance Criteria, Minimum Performance (MP)	Acceptance Criteria, Improved Performance (IP)	Acceptance Criteria, Best Performance (BP)
Steel Substrate				
Scribed Area Rating	≥ 7	≥ 6	≥ 6	≥ 6
Unscribed Area Rating	$\geq 7F$	$\geq 7F$	$\geq 7F$	$\geq 7F$
Exposure Period	336 hours	500 hours	750 hours	1000 hours

4.4.6 Chip Resistance (SAE J400)

4.4.6.1 Scope

The Chip Resistance test is designed to reproduce the effect of gravel or other media striking exposed painted and/or coated surfaces of a vehicle and has been correlated to actual field results. The purpose of this test is to evaluate the chip resistance of flat test specimens incorporating the candidate.

4.4.6.2 Equipment

Gravelometer. As specified in SAE J400 with the test panel at a 45-degree angle.

Test Cabinet. Temperature conditioning (usually run at ambient or lower temperature) with the ability to obtain and maintain the required environmental conditions as specified in SAE J400.

Transparent Grid. Approximately 3.2 x 127 x 127 mm (1/8" x 5" x 5") on which a 101.6 x 101.6 mm (4" x 4") grid of 25.4 mm (1") squares has been etched or scribed.

Paint Removal Tape. 100 mm (3.94") wide or 50 mm (1.97") wide, 3M product # 898 filament strapping tape or equivalent. *NOTE:* Note that the tape has a one-year shelf life. Utilizing the tape after this time may yield inaccurate results.

Gravel. Water-worn road gravel, not crushed limestone or rock. The gravel will pass through 15.86 mm (5/8") space screen when graded, but be retained on 9.53 mm (3/8") space screen. Gravel must be changed in accordance with SAE J400 Section 4.2.

4.4.6.3 Reagents

None.

4.4.6.4 Procedure

Test Specimen. Screening and Performance test specimens shall be panels, composed of the material that is utilized in the end application. The chipped area to be evaluated on the tested panel shall be flat and 101.6 x 101.6 mm (4" x 4") square and must be located about the center of the chipped pattern. SAE recommends that three replicates of each test panel be exposed in the Gravelometer. The composition, surface preparation, and size of panels; the type and thickness of the coating and the number and method of

application; and the aging conditions for the coatings shall be agreed upon between the vendor and invoking authority.

Test Setup/Preparation. Condition the test panels incorporating the candidate at the temperature specified in SAE J400 for a minimum of 15 minutes prior to testing. Fill a 0.473-liter (1-pt) container to the top with grated/screened gravel. Gravel must be changed every 3 runs. Adjust air pressure on the Gravelometer to 483 kilopascals (kPa) (70 psi) +/- 21 kPa (0.30 psi) with the air valve open. Set feed rate so that the hopper empties in 7–10 seconds per pint (s/pt). Other air pressures can be used as agreed upon by the vendor and invoking authority.

Test Procedure for Modular Gravelometer with Electronic Feed Mechanism. Insert the test panel into the specimen holder assembly. Clamp panel and close the specimen holder. Pour gravel from the one-pint container into hopper, then set the test timer.

a. Time Test

Set the test timer to the desired test time (typically < 10 s).

Turn the main power switch to ON.

Flip the control switch to TIME START.

b. Manual Test

See SAE J400 Section 4.2.3.2.

Chipping Rating System. The basic structure of the chipping rating system consists of one or more number-letter combinations in which rating values/numbers 10–0 indicate the number of chips of each size with rating letters A–D designating the sizes of the corresponding chips. Tables 5 and 6 provide guidelines for Rating Criteria as stated in SAE J400. A point of failure notation can also be used if desired (see Table 7).

Table 5. Rating for Number of Chips Within 4" x 4" Grid Lines

Rating Number	# of Chips	Rating Number	# of Chips
10	0	4	50–74
9	1	3	75–99
8	2–4	2	100–149
7	5–9	1	150–250
6	10–24	0	> 250
5	25–49		

Table 6. Rating for Size of Chips

Rating Letter	Size of Chips
A	< 1 mm (approximately 0.03")
B	1–3 mm (approximately 0.03–0.12")
C	3–6 mm (approximately 0.12–0.25")
D	> 6 mm (> approximately 0.25")

Table 7. Point of Failure

Notation	Level of Failure	Failure Type
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(S/P)	Substrate to Primer	Adhesional
(S/T)	Substrate to Top Coat	Adhesional
(P)	Primer	Cohesional
(P/T)	Primer to Top Coat	Adhesional
(T)	Top Coat	Cohesional

Method 1 – Exact Counting Procedure. This very precise method shall be used where definitive accuracy is required or as the referee method in case differences arise between laboratories.

- a) Use the transparent overlay onto which has been etched a 101.6 x 101.6 mm (4" x 4") grid of 25.4 mm (1") squares as a location reference to aid the counting/rating process.
- b) Examine all chips that are within each 25.4 mm (1") square, and estimate the size of each chip as encountered; examine all 16 squares and record the summed results.
- c) Convert the actual number of chips counted for each size into the number-letter combinations utilizing Tables 5 and 6. Then arrange the number-letter ratings in ascending order (by number then letter). Summarize the number-letter ratings to give a condensed single number rating based on the total number of chips of all sizes followed by all applicable letter ratings to indicate the relative number of chips of each size.

Method 2 – Visual Comparison Procedure. This faster method shall be used for many routine laboratory evaluations where accuracy is not required.

- a) Visually compare the area to be rated with the standards (SAE J400, Figure 3).
- b) As with Method 1, list the ratings in ascending order. Summarize the number-letter ratings to give a condensed single number rating based on the total number of chips of all sizes followed by all applicable letter ratings to indicate the relative number of chips of each size.

Test Results. Visually evaluate the resistance of the coating surface to chipping by gravel impact using the transparent grid and the rating scheme (Tables 5, 6 and 7, and Method 1 and Method 2).

Reports. Report the summarized number-letter rating and all applicable test conditions. In addition, report the substrate material type and thickness; any preliminary surface treatment of test panels; the type of surface coatings; baking/aging or pertinent processing schedules; and the film thickness of the coating system being evaluated.

4.4.6.5 Acceptance Criteria

Substrate	Acceptance Criteria, Minimum Performance (MP)	Acceptance Criteria, Improved Performance (IP)	Acceptance Criteria, Best Performance (BP)
Steel	After one cycle, chip rating not less than 5B	After one cycle, chip rating not less than 7C	After one cycle, chip rating not less than 9C

4.4.7 Rising Step Load (Stress Corrosion Cracking)

4.4.7.1 Scope

Hydrogen embrittlement testing shall be performed on any candidate that is considered a risk candidate. Resistance to environmentally assisted cracking shall be assessed using the rising step load method for determination of K_IEAC. For this procedure, CV2 Charpy specimens of MIL-A-46100D shall be machined in longitudinal-transverse (L-T) and transverse longitudinal (T-L) orientations in accordance with ASTM E 399-97. Unlike the armor test panels, the charpy specimens shall not be abrasive blasted prior to pretreatment.

4.4.7.2 Equipment

The equipment shall be determined by the applicable test method.

4.4.7.3 Reagents

The reagents shall be as described in the applicable test method.

4.4.7.4 Procedure

Specimen fatigue precracking shall be carried out using three stages, each consisting of decreasing loading levels. In the first precracking stage, the load was maintained to keep stress intensity values below 80% of the estimated experimental critical stress intensity and the stress ratio ($\sigma_{\text{max}}/\sigma_{\text{min}}$) was kept between -1 and +0.1. In the intermediate stage, the cycling load shall be reduced to maintain the stress intensity value as crack growth occurred and the intact cross section was reduced. For the final stage of precracking, the load shall be further reduced so the final value of K_{max} will unlikely exceed 60% of the estimated value for K_I during experimentation. Additionally, the final value for K_{max}/E should not exceed 0.0032 m^{1/2}, where E is Young's modulus. Precrack length, represented by the dimensionless expression a/W (crack length over specimen width), shall be maintained near 0.5.

Specimens shall be fastened into a double cantilever array test fixture under aqueous conditions with 3.5% NaCl solution at open circuit potential conditions. Specimens shall be loaded by incremental steps in accordance with ASTM F 1624-95 (26) using an appropriate load frame apparatus. The specimen load values versus time shall be recorded. The calculation for the onset of environmentally assisted cracking, or K_IEAC, is derived as follows for cantilever bending from the four-point bending expression.

$$K_{IEAC} = \left(\frac{6M_{IEAC}\sqrt{\pi a}}{BW^2} \right) \times f(a/W)$$

4.4.8 Field Exposure, Static (ASTM G50)

4.4.8.1 Scope

This test method describes a basic procedure for conducting outdoor testing of specimens incorporating of candidates for GVFSs.

4.4.8.2 Equipment

Standard Racks. See Section 5 of ASTM G50.

Scribe Tool. An ANSI B 94.50, style E scriber.

Straightedge. Any straightedge of sufficient length to guide the scribing tool in a straight line.

Balance. A digital electronic balance capable of weighing up to 10,000 mg with an accuracy of +/- 1%.

4.4.8.3 Reagents

Cleaning Solution. Methanol.

4.4.8.4 Procedure

Test Specimens. Prepare at least 10 specimens consisting of sections of actual GVFSs or manufactured parts that accurately simulate current production material and manufacturing processes, incorporating the candidate, and 10 specimens incorporating the current corrosion protection system. Each test specimen and reference coupon shall contain a clear identification mark. Use reference coupons consisting of uncoated 25 x 51 x 3 mm (1" x 2" x 1/8") pieces of any alloy AISI 1006 through 1010 steel to monitor the average general bare steel corrosion produced by the test track environment. The reference coupons shall be thoroughly cleaned using the cleaning solution. The coupon weight in milligrams shall be recorded and retained for future reference.

Test Sites. Test sites shall be chosen at a number of locations representative of the atmospheric environments where the military vehicle is likely to be used.

Preparation. Using test specimens incorporating the candidate and the current corrosion protection system, scribe a single diagonal line making sure that the scribed line is all the way through the coating into the substrate.

Test Procedure. Attach the test specimens and reference coupons to the racks at the approved test site and test in accordance with the test site standard practice, ASTM G50, "Standard Practice for Conducting Atmospheric Corrosion Tests on Metals". ASTM G50 recommends a multi-year exposure period to minimize the variability of environmental (industrial and natural) factors influencing the atmospheric corrosivity of a test site.

Monitor environmental factors in accordance with ASTM G50. Evaluate the performance of the candidate and current corrosion protection system test specimens, and reference coupons at six-month intervals and at the completion of the exposure period. At the end of the exposure period, clean the reference coupons using a mild sand (or glass bead) blast to remove all corrosion by-products.

Test Results. Inspect the test specimens and reference coupons for any signs of degradation. Measure scribe creep in accordance with ASTM D1654. Once clean, wipe coupons with methanol and weigh to determine weight loss. Corrosion losses may also be expressed in terms of average corrosion rates from the weight loss, coupon area, test duration, and metal density by use of the calculation described in ASTM G1.

Report. Report observations in accordance with the test site standard practice, ASTM G50, including environmental factors monitoring, and weight loss and/or corrosion rate of the reference coupons.

4.4.8.5 Acceptance Criteria

Test	Acceptance Criteria, Minimum Performance (MP)	Acceptance Criteria, Improved Performance (IP)	Acceptance Criteria, Best Performance (BP)
Field Exposure, Static	Three years of exposure: specimen has a minimum of 25% less creepage from scribe than current corrosion protection system	Four years of exposure: specimen has a minimum of 50% less creepage from scribe than current corrosion protection system	Five years of exposure: specimen has a minimum of 75% less creepage from scribe than current corrosion protection system

4.4.9 Field Exposure, On-Vehicle (ASTM D 1654)

4.4.9.1 Scope

This test method describes a basic procedure for conducting on-vehicle testing of candidates. This may be performed by selective replacement or refinishing of an appropriate representative substrate/component on a vehicle incorporating the candidate, or by the use of test specimens incorporating the candidate attached to the military ground vehicle.

4.4.9.2 Equipment

Military Ground Vehicle. A vehicle used for standard deployment.

4.4.9.3 Reagents

Cleaning Solution. Materials required as designated by each candidate supplier.

4.4.9.4 Procedure

At a minimum, the process shall be conducted to replace or refinish a part or section of the vehicle in accordance with the suggested finishing parameters and the controls established by the CARC applications specification MIL-DTL-53072. If using test panel, they shall be prepared in

accordance with above G50 for static field testing and evaluated using ASTM-D 1654. Representative substrates/components will be pretreated in accordance with pretreatment manufacturers recommended specifications finishing parameters and controls established in MIL-DTL-53072. Components substrates will be evaluated during periodic inspections by visual comparison with the base vehicle or control samples attached to the vehicle. The Society for Protective Coatings SSPC-VIS-2 “Standard Method for Evaluating the Degree of Rusting on Painted Steel Surfaces” shall be used for evaluating component substrates and control samples. The success criteria for field testing will be performance greater than or equal to the base vehicle (baseline) or control sample.

Report. After a predetermined exposure agreed upon by the stakeholders, the affected vehicles/parts shall be evaluated for coating adhesion, color, and corrosion resistance in accordance with SSPC-VIS-2, MIL-DTL-53072 and ASTM D 1654.

5.0 FAILURE ANALYSIS

To be considered for use as a replacement for the current corrosion protection system, a candidate must pass all tests. The failure of any Screening, Performance, or Special Test shall be documented in the JTR. At the candidate vendor's request and expense, a failure analysis procedure can be undertaken to determine the failure mechanisms. Such failure analysis can be a useful vendor option to identify and correct failure mechanisms prior to retesting. However, after failing any of the Screening, Performance, or Special Tests for the third time, further iterations of that test are not permitted. Instead, the JTP process shall be ended and the results noted in the JTR. The JTR shall then be forwarded to the vendor for transmittal to the invoking authority for review.

In the event of any testing-related dispute between vendor and tester, such as causes of premature failure, a third-party testing lab will be mutually agreed upon as a credible testing source by the invoking authority. This Product Failure Laboratory (PFL) must have no pre-existing connections to either the vendor of the candidate or the original laboratory that conducted the testing. The process flow is illustrated in Figure 1, which appears in Section 2.0, JTP Document Guide.

Marginal test results must be either overcome by retesting or documented before rejecting/failing the candidate. Failure in any test does not necessarily disqualify a candidate for use in all possible applications.

The initial JTR and all related JTRs (specifically those documenting failure analyses) shall be submitted to the vendor for transmittal to the invoking authority for review.

6.0 REFERENCE DOCUMENTS

The documents listed in Table 8 were referenced in the development of this JTP.

Table 8. Reference Documents

Reference Document	Title	Applicable Section(s) of Reference Document	JTP Test	JTP Section Cross-Reference	Document Source
ASTM B117	Standard Test Method of SS (Fog) Testing	All	Corrosion Resistance NSS (Fog)	4.4.3	ASTM
ASTM D714	Test Method for Evaluating Degree of Blistering of Paints	All	Corrosion Resistance NSS (Fog) Corrosion Resistance (Cyclic) Field Exposure, on-Vehicle	4.4.3 4.4.4 4.4.12	ASTM
ASTM D1193	Specification for Reagent Water	All	All	All	ASTM
ASTM D1654	Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments	All	Corrosion Resistance NSS (Fog) Corrosion Resistance (Cyclic) Seawater Immersion Field Exposure, Static Field Exposure, On-Vehicle Corrosion Resistance (Modified Salt/SO ₂ Spray (Fog))	4.4.3 4.4.4 4.4.5 4.4.11 4.4.12 4.4.13	ASTM
ASTM D3359	Standard Test Methods for Measuring Adhesion by Tape Test	All	Adhesion (Dry) Adhesion (Wet)	4.4.1 4.4.2	ASTM
Federal Specification TT-C-490D	Cleaning Methods for Ferrous Surfaces and Pretreatments for Organic Coatings	3.5.9 3.5.10	Hydrogen Embrittlement	4.2	DoD
GM 9540P	Cosmetic Corrosion Lab Test	All	Corrosion Resistance (Cyclic)	4.4.4	SAE
SAE J400	Test for Chip Resistance of Surface Coatings	All	Chip Resistance at -29° Celsius	4.4.6 4.4.14	SAE
MIL-DTL-53072	Chemical Agent Resistant Coating (CARC) System Application Procedures And Quality Control Inspection	All	All		

APPENDIX

LIST OF STAKEHOLDERS AND LIST OF CONTRIBUTORS

List of Stakeholders

FIRST NAME	LAST NAME	ORGANIZATION	ADDRESS	CITY/STATE/Z IP	PHONE	FAX	E-MAIL
Steve	Bails	SBCT		Warren MI 48397-5000	586-282-7886		Stephen.Bails@us.army.mil
Todd	Weimer	PEO-CS-CSS, MRAP	SFAE-CSS-MR-E	Warren MI 48397-5000	(586) 282- 2679	(586) 282- 2978	todd.p.weimer@us.army.mil
Jack	Kelley	ARL	RDRL-WMM-C	Aberdeen Proving Ground, MD 21005-5059	410-306-0837	410-306-0829	Jack.kelley1@us.army.mil
Thomas	Braswell	ARL	RDRL-WMM-C	Aberdeen Proving Ground, MD 21005-5059	410-306-0935	410-306-0829	Thomas.e.braswell@us.army.mil
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Amy	Fowler	NAVAIR	NAVAIR, Code 4.3.4.2 48066 Shaw Road, Bldg. 2188	Patuxent River, MD 20670	301-342-0986	301-342-7566	amy.fowler1@navy.mil
Brian	Placzankis	ARL	RDRL-WMM-C	Aberdeen Proving Ground, MD 21005-5059	*	*	*
Andrew	Sheetz	NSWCCD	9500 MacArthur Blvd, Code 6130	West Bethesda, MD 20817-5700	*	*	*
John	Escarsega	ARL	RDRL-WMM-C	Aberdeen Proving Ground, MD 21005-5059	*	*	*
Chris	Miller	ARL	RDRL-WMM-C	Aberdeen Proving Ground, MD 21005-5059	*	*	*
Carl	Handsy	TACOM	6501 E Elenen Neil Rd, AMSTA-TR- E1 MEPS1267	Warren, MI 48397-5000	*	*	*

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Appendix B. Points of Contact

Point of Contact Name	Organization Name Address	Phone Fax E-mail	Role in Project
Jack Kelley	U.S. Army Research Laboratory B4600, Deer Creek Loop Aberdeen Proving Ground, MD	PH: 410-306-0837 FX: 410-306-0829 BB: 240-429-8485 jkelley@arl.army.mil	Project lead
Tom Braswell	U.S. Army Research Laboratory B4600, Deer Creek Loop Aberdeen Proving Ground, MD	PH: 410-306-0935 FX: 410-306-0829 Thomas.e.braswell@arl.army.mil	Testing and specifications
Amy Fowler	NAVAIR, Code 4.3.4.2 48066 Shaw Road, Bldg. 2188 Patuxent River, MD 20670	PH: 301-342-0986 FX: 301-342-7566 amy.fowler1@navy.mil	TCP technology development
Luwam Hagos	NAVAIR, Code 4.3.4.2 48066 Shaw Road, Bldg. 2188 Patuxent River, MD 20670	PH: (301)342-8159 FX: (301)342-8062 luwam.hagos@navy.mil	Navy co-performer
Patricia Dodson	Patty Dodson Anniston Army Depot 7 Frankford Avenue Bldg. 106 Anniston, AL 36201	Patricia.dodson@us.army.mil COMM: 256-235-6700	Coordinate demonstration at Anniston
James Swann	Jacobs-ASG PM SBCT LNO-ANAD Anniston Army Depot Anniston, AL 36201	com: 256-235-7408 DSN: 571-7408 BB: 586-219-4352 James.swann1@us.army.mil	Stryker demonstration coordinator

Appendix C. Health and Safety Plan (HASP)

The HASP for the demonstration of steel conversion coatings on Stryker components conducted at the Anniston Army Depot, AL, will follow the guidelines contained in ANADR-385-1.¹ Applicable sections of ANADR-385-1 will be reviewed by members of the Stryker demonstration team prior to conducting the demonstrations.

C.1 Personal Protective Clothing and Equipment

C.1.1 Eye Protection

Eye hazardous tasks are any tasks which expose the worker to a reasonable possibility of an eye injury from dust, shavings, other flying particles, liquid chemicals, acids or caustic liquids, chemical gases or vapors, molten metal, hazardous glare, or radiation.

1. Safety eye wear will be worn by all employees who enter eye hazard areas or perform eye hazardous tasks.
2. When an employee suffers an eye injury, the supervisor must state on the CA-1 and dispensary pass if safety eyewear was required for the job being performed and if the eyewear was being worn.
3. All safety glasses will be issued with side shields. Side shields must be used at all times. Tasks that involve chemicals or fine particles call for the use of chemical splash goggles, not safety glasses.
4. Safety eyewear shall be distinctly marked to facilitate identification of the manufacturer.
5. Photo grey lenses are not authorized because the tint change is relatively slow and inconsistent.
6. Any person having useful vision in only one eye will be furnished with and required to wear safety glasses while in a shop or field environment.
7. Contact lenses do not meet the requirements of eye protection. A person wearing contact lenses must use some form of eye protection when in a hazardous area.
8. No person wearing contact lenses will be allowed to work in areas where chemicals, fumes, vapors, dusts, particles, or molten metals are present.
9. A face shield should be used in conjunction with eye protection to protect the face from chemicals, particles, or other material such as banding steel.

¹ Headquarters, U.S. Army Corps of Engineers. *Safety and Health Requirements Manual*; EM 385-1; Anniston Army Depot: Anniston, AL, 3 June 2005.

C.1.2 Foot Protection

1. Employees shall wear protective footwear when working in areas where there is a danger of foot injuries due to falling and rolling objects or objects piercing the sole.
2. Sandals, canvas shoes, cloth shoes, or similar types will not be worn in shops or warehouse areas.
3. It is the employee's responsibility to select safety shoes that fit properly to preclude foot discomfort.
4. Personnel who work upon conductive flooring, conductive mats, or conductive runners where explosives or flammable vapors are present must wear nonsparking, conductive footwear. Personnel from other departments or visitors who enter these areas and who walk on conductive flooring materials must also wear nonsparking conductive footwear. Leg stats are acceptable for visitors or transients and can be used in toxic chemical operations as long as their basic footwear is of nonsparking construction. Under no circumstances will personnel working on electrical equipment or facilities wear conductive-sole safety shoes or other conductive footwear.
5. For all operations involving explosives not susceptible to static spark of the energy that can be discharged from a person, sparkproof (nonspark-producing) shoes are required. Shoes with soles and heels of leather, rubber, or synthetic compositions (neelite, neoprene, and similar compositions) may be used provided the soles and heels contain nonexposed nails or holes. The shoes shall have a fully enclosed safety toe cap. The soles and heels must be cleaned free from sand and dirt before entering a building containing explosives.
6. Under emergency circumstances, conductive shoes may be used as a substitute provided they are closely examined and tested after this use and electric current sources are guarded or shut off in the operation area.

C.1.3 Respiratory Protection

In the control of those occupational diseases caused by breathing air contaminated with harmful dusts, fogs, fumes, mists, gases, smokes, sprays, or vapors, the primary objective shall be to prevent atmospheric contamination. This shall be best accomplished by accepted engineering control measures (i.e., enclosure or confinement of the operation, general and local ventilation, and substitution of less toxic materials).

Respiratory protection will only be used as a means of controlling employee exposure to airborne environmental hazards under the following circumstances:

- When no engineering or work practice controls can be used to adequately control the hazard.
- During intermittent or nonroutine operations.

- During interim periods while engineering controls are being designed and installed to eliminate the hazard.
- During emergencies.

C.2 Hazardous Materials

C.2.1 Labeling

The precautionary label for any hazardous chemical will be based upon the hazard it possesses. Containers of hazardous chemicals will be labeled in accordance with ANSI 129.1² and 29 CFR 1910.1200³. At a minimum, they will contain the following:

- Identity of hazardous chemical.
- Appropriate hazard warnings.
- Name/manufacturer, importer, or other responsible party.
- Precautionary measures (first aid).

Precautionary labels will be affixed to containers of hazardous material to afford easy and quick recognition of associated hazards.

Vehicles transporting hazardous chemicals will have placards corresponding to the warning label on the container to alert persons to potential dangers associated with the hazardous chemicals contained in the vehicle, and the driver will be briefed concerning the hazardous material transported.

C.2.2 Responsibilities

Employees will be provided information and training on hazardous chemicals in their work areas at the time of their initial assignment and whenever a new hazardous chemical is introduced into their work area. Responsibilities will include, but are not limited to the following:

- Obtain material safety data sheets (MSDSs) for hazardous chemicals when requested by the user, and forward a copy of the MSDS to the user as requested.
- Review MSDSs, process control pamphlets, and local standard operating procedures, become familiar with the hazards associated with the chemical being handled, and know first aid and emergency procedures.
- Follow proper storage and handling procedures.
- Report all leaks or spills of hazardous chemicals to the immediate supervisor.

² ANSI Z400.1/Z129.1-2010. *Hazardous Workplace Chemicals - Hazard Evaluation and Safety Data Sheet and Precautionary Labeling Preparation*, 2010.

³ Occupational Safety and Health Administration. *Hazard Communication*; 29 CFR 1910.1200; Washington , DC, 25 May 2012.

C.3 Medical Facility

The Springfellow Memorial Hospital is located in Anniston, AL, on 301 E. 18th St. (Telephone: 256-235-8900.)



Figure C-1. Location of Springfellow Memorial Hospital.

C.3.1 Driving Directions to Hospital

Turn right toward Roosevelt Dr. and go 0.3 mi. Continue straight onto Roosevelt Dr., go 0.2 mi, and turn left toward Eulaton Gate Rd. Continue straight onto Eulaton Gate Rd. and go 0.7 mi. Turn left at Bynum Leatherwood Rd./Co Rd. 109 and go 0.8 mi. Turn left at AL-202 E/Albert P Brewer Hwy. Continue to follow AL-202 E for 4.5 mi. Continue onto W 8th St. and go 0.3 mi. Turn left at Quintard Ave. and go 0.9 mi. Turn right at E 18th St. Hospital will be on the left.

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**Appendix D. Memo Between the U.S. Army Research Laboratory and the
Program Managers Office (PMO) Stryker Brigade Combat Team**

This appendix appears in its original form, without editorial change.



DEPARTMENT OF THE ARMY
US ARMY RESEARCH, DEVELOPMENT AND ENGINEERING COMMAND
ARMY RESEARCH LABORATORY
ABERDEEN PROVING GROUND MD 21005-5069

MEMORANDUM OF AGREEMENT
BETWEEN
THE U.S. ARMY RESEARCH LABORATORY,
WEAPONS AND MATERIALS RESEARCH DIRECTORATE
AND
PMO STRYKER BRIGADE COMBAT TEAM

SUBJECT: ARL and PM-SBCT MOA

1. REFERENCES:

a. Annex A: Enhanced Coatings and Products for Environmental Compliance and Durability.

b. Annex B: PMO Stryker Brigade Combat Team Corrosion Prevention and Control Plan

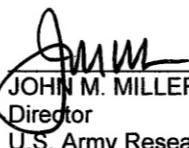
2. PURPOSE: To formalize the longstanding partnership between ARL and PMO SBCT Environmental Management Team for environmental compliance, enhanced materials, advanced coatings, improved processes at OEM and depot facilities, and technical support for the PMO Stryker Brigade Combat Team Corrosion Prevention and Control Plan.

3. PROBLEM: Environmental degradation of fielded Stryker assets and ever changing environmental regulatory policies from local, national, and international sources.

4. SCOPE: ARL and SBCT will follow the guidelines agreed upon under Annex A.

5. CHANGES/TERMINATION: Changes or termination may be made by mutual agreement and/or negotiations between both organizations with 90 days written notice. Changes will be documented by modifications to this plan.

6. EFFECTIVE DATE: Nov 1, 2007.


JOHN M. MILLER
Director
U.S. Army Research Laboratory


KEVIN M. FAHEY
Program Executive Officer
Ground Combat Systems

List of Symbols, Abbreviations, and Acronyms

ANAD	Anniston Army depot
ARL	U.S. Army Research Laboratory
CARC	chemical agent resistant coating
DI	deionized
DOD	U.S. Department of Defense
DRCF	depot repair cycle float
EAC	environmentally assisted cracking
ECAM	environmental cost analysis methodology
ESTCP	Environmental Security Technology Certification Program
HASP	Health and Safety Plan
HazMat	hazardous material
HHA	high hard armor
IAW	in accordance with
JTP	joint test protocol
MRAP	mine-resistant, ambush-protected armored vehicles
MSDS	material safety data sheet
NAVAIR	U.S. Naval Air Warfare Center
NDCEE	National Defense Center for Energy and Environment
OEM	original equipment manufacturer
OSHA	Occupational Safety and Health Administration
PEL	permissible exposure limit
PEO	Program Executive Office
PEP	power entry panel
PM	Program Manager

PMO	Program Managers Office
PPG	Pittsburgh Plate and Glass
RTU	ready to use
SAE	Society of Automotive Engineers
SBCT	Stryker brigade combat team
SCC	stress corrosion cracking
SERDP	Strategic Environmental Research and Development Program
SSPC	Society for Protective Coatings
TCP	trivalent chrome pretreatment
VOC	volatile organic compound

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